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Supplemental Information On A Conceptual Design Of A Space-Based Multimegawatt MHD Power System

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SUPPLEMENTAL INFORMATION ON THE CONCEPTUAL DESIGN OF A SPACE-BASED MULTIMEGAWATT MHD POWER SYSTEM

Prepared For

WESTINGHOUSE

FEBRUARY 1988

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LIST OF ACRONYMS

ACES	Action Commitment Expediting System
AESD	Advanced Energy Systems Division
ALS	Advanced Launch System
APT	Advanced Power Train
β	Hall parameter
BAC	Boeing Aerospace Company
CD	Control Drum
CDIF	Component Development and Integration Facility
CSS	Core Structural Support System
DOD	United States Department of Defense
DOE	United States Department of Energy
EFPS	Effective Full Power Seconds
EMI	Electromagnetic Interference
EML	Electromagnetic Launchers
EUT	Eindhoven University of Technology
FEL	Free Electron Lasers
GTO	Gate Turn Off Device
HEL	High Energy Lasers
IMACS	Integrated Management and Control System
INEL	Idaho National Engineering Laboratory
IUS	Inertial Upper Stage
LANL	Los Alamos National Laboratory
MHD	Magnetohydrodynamic
MIT	Massachusetts Institute of Technology
MMW	Multimegawatt
NDR	NERVA Derivative Reactor
NERVA	Nuclear Engine for Rocket Vehicle Application
NPB	Neutral Particle Beam
OMV	Orbital Maneuvering Vehicle

LIST OF ACRONYMS (Continued)

PCS	Power Conditioning System
PETC	Pittsburgh Energy Technology Center
R&D	Research and Development
SDI	Strategic Defense Initiative
SDIO	Strategic Defense Initiative Organization
SPA	System Performance Analysis
STS	Space Transportation System
TIT	Tokyo Institute of Technology
WBS	Work Breakdown Structure

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1.0 INTRODUCTION

The objective of this project is to perform a feasibility assessment of space-based multimegawatt (MMW) magnetohydrodynamic (MHD) power systems for Strategic Defense Initiative Organization (SDIO) mission applications and to resolve technical uncertainties that may impact their future implementation.

The ultimate goal of the SDIO is to provide security for the United States and its allies. The near-term objective of the SDIO is to conduct research on those technologies for defensive systems that might be capable of intercepting ballistic missiles after launch and preventing them from hitting their targets.

System concepts currently being considered for space-based weapons applications will, if implemented, require specially tailored power systems. These power systems may possess characteristics and specifications lying considerably outside the design range of conventional devices. Their development may require major advances in existing technology and the accelerated development of entirely new approaches.

Numerous weapon devices for SDIO applications have been proposed: Electromagnetic Launchers (EML), Free Electron Lasers (FEL), Neutral Particle Beams (NPB), and High Energy Lasers (HEL), among others. Generally, these devices require efficient, lightweight, compact and reliable power systems, which for certain operating modes, must be capable of generating high levels of burst power (100s of MW) for extended periods (1,000s of seconds). The location and intended use of the weapons implies that the subject power system must function reliably under hostile circumstances. MHD power generation is a particularly promising technology for this type of application. Accordingly, an MHD technology feasibility assessment program has been initiated.

This feasibility assessment program is divided into two phases. In the first phase, an MHD power system concept will be selected, technical uncertainties will be defined, plans to address those technical uncertainties will be developed, and tests will be conducted to resolve technical uncertainties.

This first phase assessment is divided into two tasks. In Task 1, a nuclear disk MHD generator power system conceptual design has been selected, technical uncertainties associated with this system have been identified and plans to resolve these uncertainties have been developed. Task 2 of Phase 1 will involve implementation of the plans developed in Task 1, subject to approval by DOE PETC to proceed.

This report supplements the Topical Report WAESD-TR-88-002, "Conceptual Design of a Space-Based Multimegawatt MHD Power System," (January 1988) in the following areas: design and performance, cost, spacecraft integration, power conditioning, and subsystem/component development and testing. The effort expended in preparing the information in this supplemental report and the report itself was performed using AESD discretionary funds.

2.0 SYSTEM ENGINEERING AND COMPONENT DESCRIPTION

2.1 Introduction

The configuration of the selected space-based multimegawatt nuclear disk MHD power system concept is discussed. This system concept was configured to meet mission, functional and system integration requirements discussed in the Task 1 topical report(2-1). The objective of the effort reported here is to describe and discuss in some detail the key elements of the space-based nuclear powered disk MHD power system concept and provide preliminary configuration and dimensional information for estimating the mass and cost of the disk MHD generator.

2.2 System Description

The overall space-based nuclear disk MHD power system is depicted in Figure 2-1 as it is conceived for the power source for a NPB system application. The reference power system overall dimensions, mass and center of gravity locations for an assumed NPB application are noted. The power system overall length and diameter are 8.5 m and 4.8 m, respectively, if a spherical LH_2 tank is incorporated. The actual power conversion system is 3.8 m long and 3.6 m in diameter, with a dry mass of 7.9 metric tons, excluding the power conditioning system.

The general layout of the power system is shown in Figure 2-2 with overall dimensions and component arrangement identified. A schematic of the flow path and key statepoint data are presented in Figure 2-3. The overall power system launch mass and cost estimates, less the power conditioning system, are 13,600 kg and $13.2 M. The bases for these estimates are indicated in the following component discussions.

(2-1) WAESD-TR-88-0002, Conceptual Design of a Space-Based Multimegawatt MHD Power System, Task 1 Topical Report, January 1988.

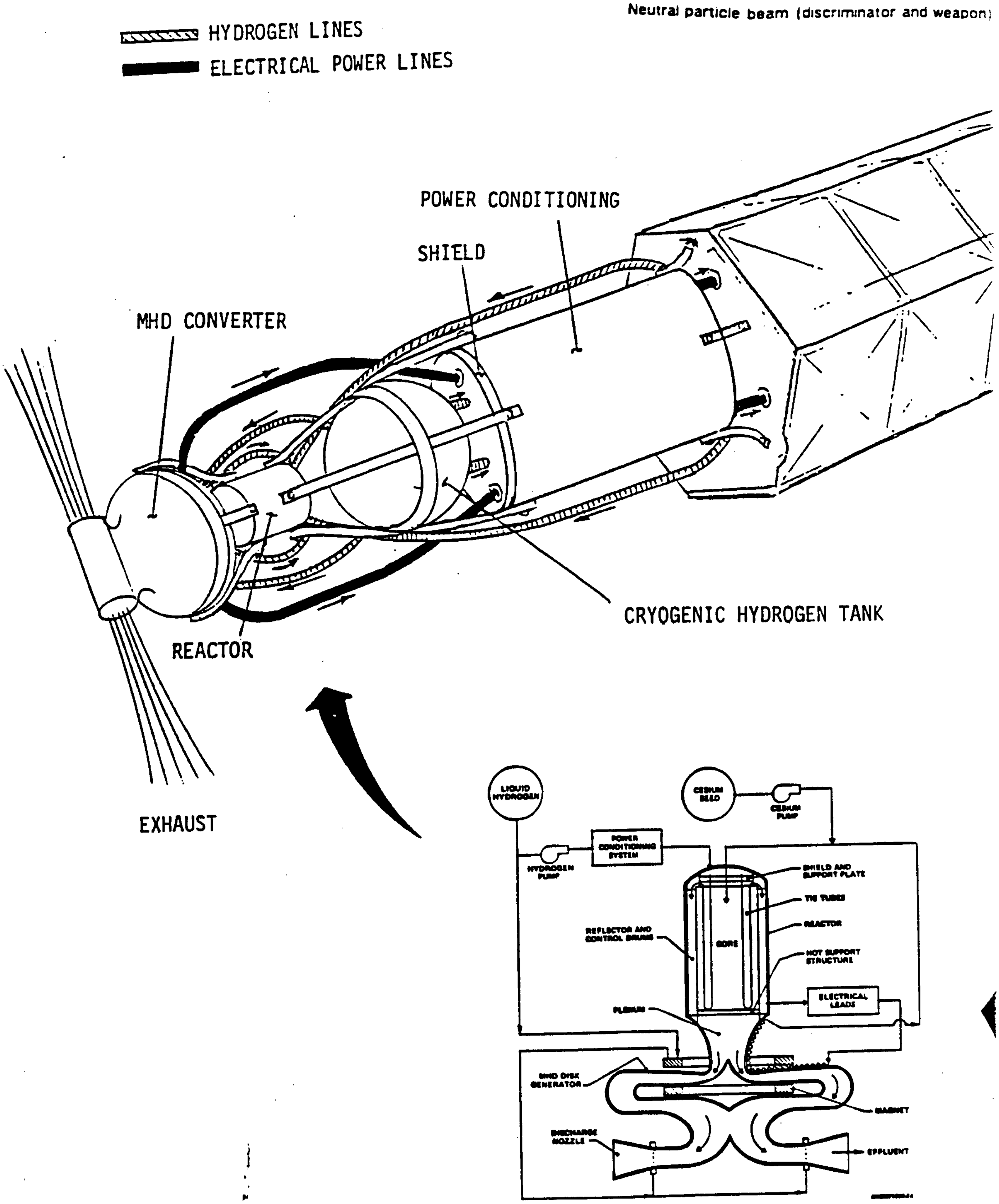
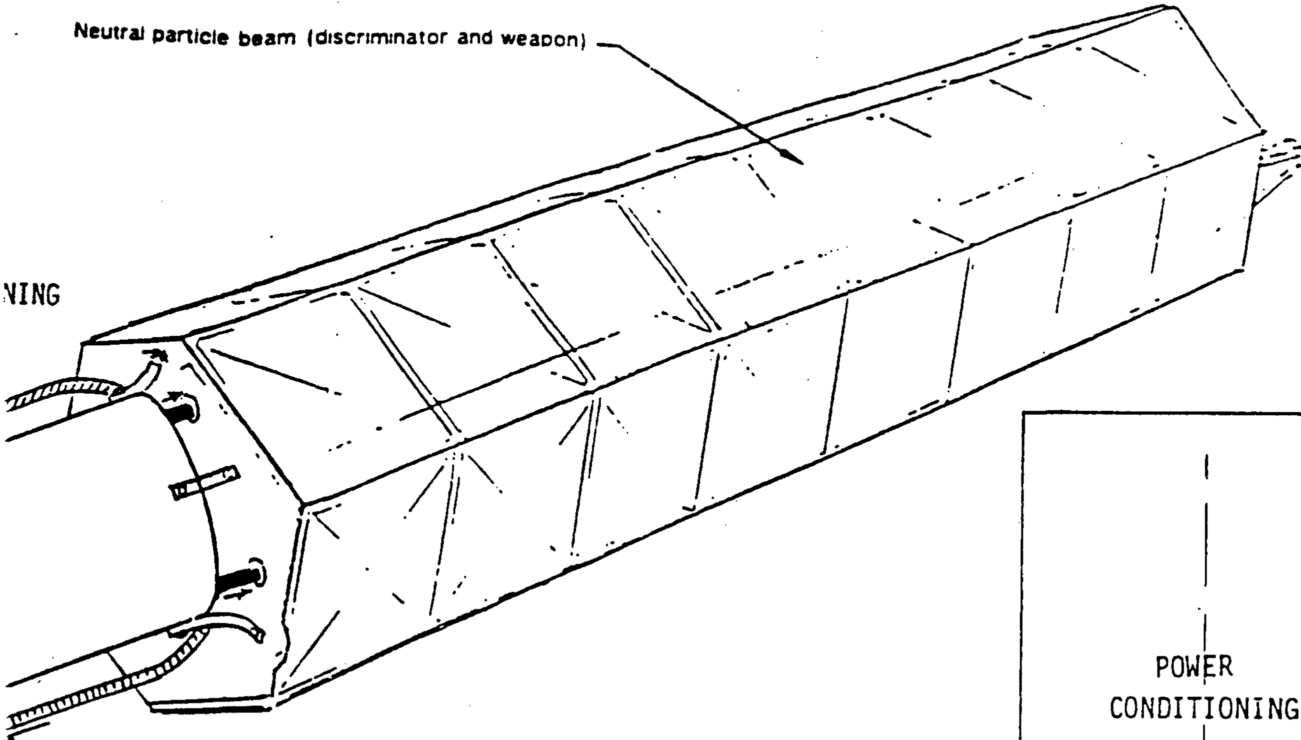
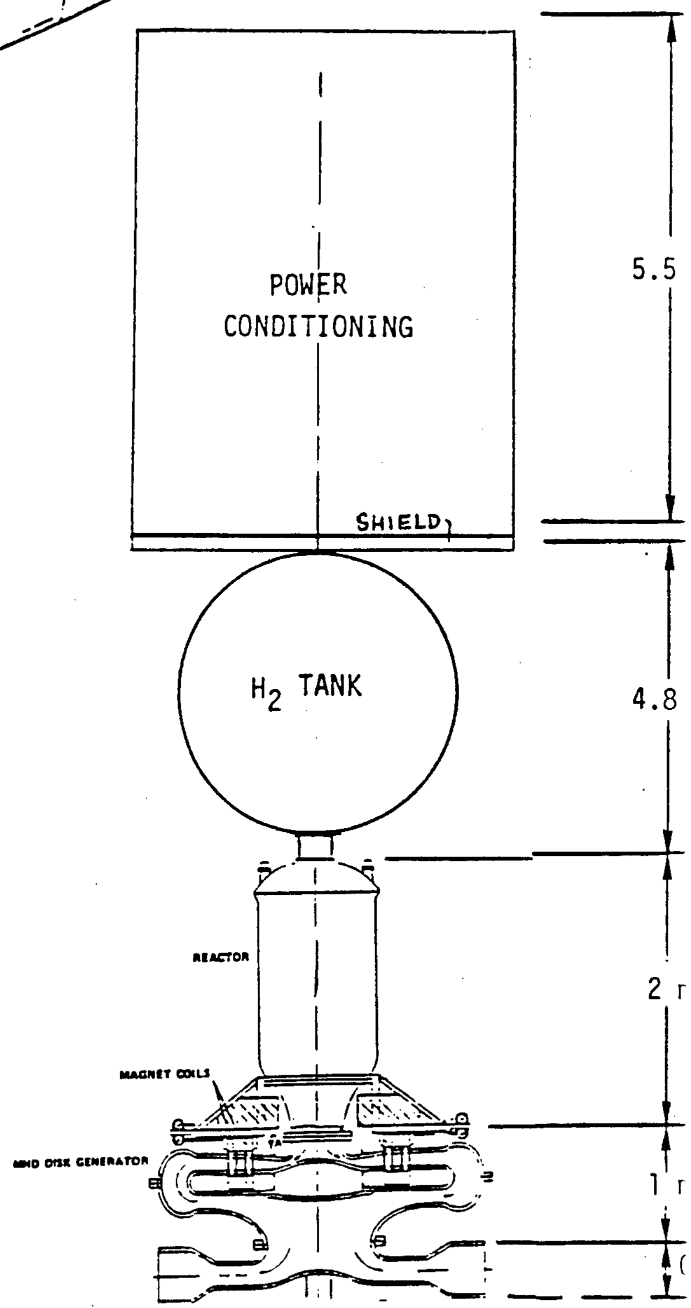


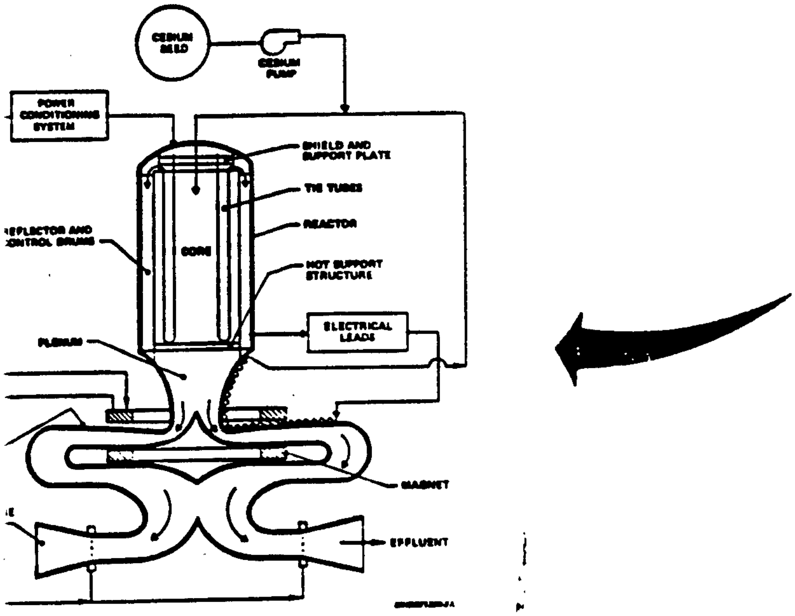
Figure 2-1. Perspective Sketch of Multimegawatt Space Nuclear Power Supply



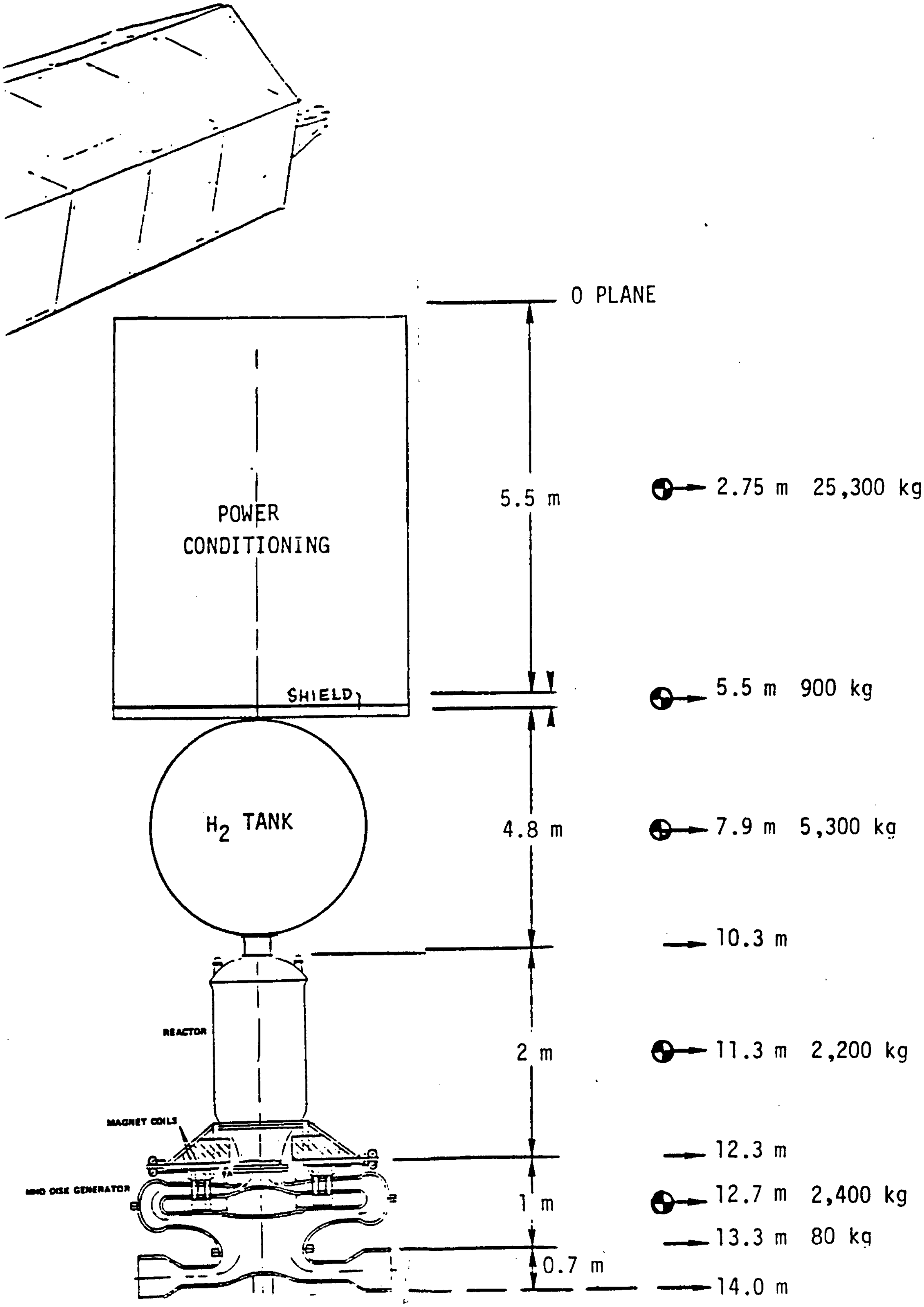
NING

CRYOGENIC HYDROGEN TANK





imegawatt Space Nuclear Power Supply


O PLANE
POWER CONDITIONING
SHIELD
H$_2$ TANK
REACTOR
MAGNET COILS
MHD DISK GENERATOR
5.5 m
4.8 m
2 m
1 m
0.7 m
2.75 m 25,300 kg
5.5 m 900 kg
7.9 m 5,300 kg
10.3 m
11.3 m 2,200 kg
12.3 m
12.7 m 2,400 kg
13.3 m 80 kg
14.0 m

3

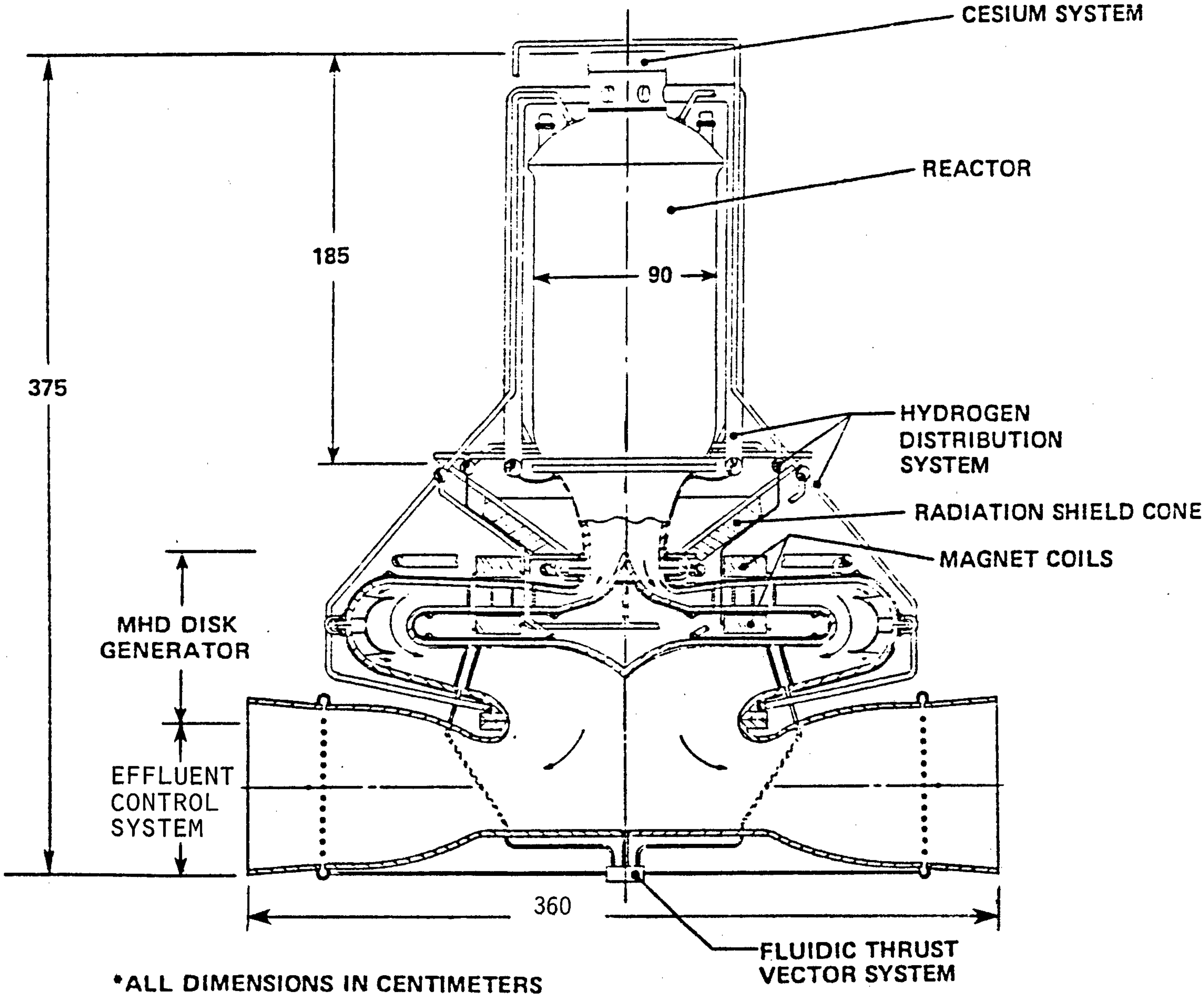


Figure 2-2. Layout and Overall Dimension of Power Conversion Subsystem

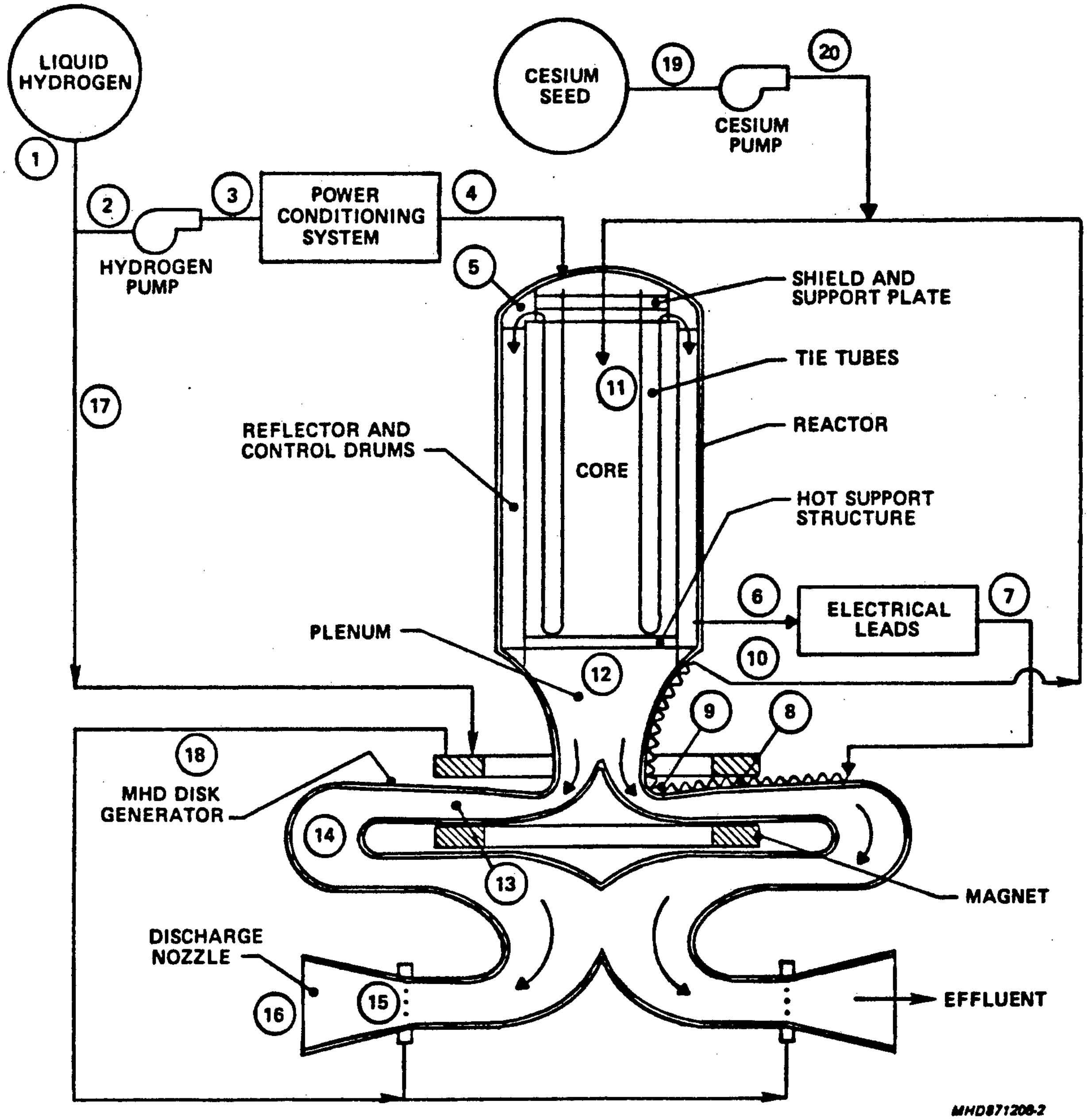


Figure 2-3. Power System Schematic Showing Statepoints

#	Location	C_s Mol Fr	W (kg/s)	P_{tot} (Atm)	T_{tot} (K)
1	H_2 Tank Outlet	0	5.530	1.00	20
2	H_2 Pump Inlet	0	5.452	1.00	20
3	Power Conditioning System Cooler Inlet	0	5.452	63.2	27
4	Core Support Structure Cooler Inlet	0	5.452	61.2	73
5	Reflector and Control Drum Cooler Inlet	0	5.452	51.2	413
6	Electrical Lead Cooling Inlet	0	5.452	46.6	532
7	2nd Section Disk Generator Cooler Inlet	0	5.452	45.6	567
8	1st Section Disk Generator Cooler Inlet	0	5.452	41.6	576
9	Reactor Lower Plenum Cooler Inlet	0	5.452	37.6	613
10	Seed Mixer Inlet	0	5.452	36.6	65
11	Reactor Core Inlet	5.0×10^{-5}	5.470	36.6	650
12	Disk Generator Inlet Nozzle	5.0×10^{-5}	5.470	16.6	2900
13	2nd Section Disk Generator Inlet	5.0×10^{-5}	5.470	0.71	2170
14	Thrust Vector Control Section Inlet	5.0×10^{-5}	5.470	0.25	1880
15	Exit Nozzle Inlet	4.9×10^{-5}	5.548	0.25	1850
16	Effluent Flow	4.9×10^{-5}	5.548		
17	Magnet Cooler Inlet	0.0	0.078	1.0	20
18	Effluent Thrust Vector Control Inlet	0.0	0.078	0.8	20
19	Cesium Pump Inlet	1.0	0.018	1.0	650
20	Seed Mixer Inlet	1.0	0.018	50	679

Figure 2-3. Power System Schematic Showing Statepoints (Continued)

The power system functional elements, excluding the power conditioning system, are defined in the following subsystems:

- reactor heat source
- shielding
- fuel storage and handling
- cesium seed storage and handling
- disk MHD generator
- magnet
- cooling and heat rejection
- diffuser and effluent control
- energy storage
- instrumentation and control

The anticipated levels of component mass are indicated in Figure 2-4. From these estimates, the level of effort for reducing mass and cost can be weighed as a function of the most significant components impacting mass and cost as noted. These will be discussed in the sections that follow.

2.3 Reactor Heat Source

The NDR heat source is designed to provide a wide range of power and pressure levels with no significant impact on mass or cost. This application provides two independent heat removal paths which serve two separate decay heat removal systems. The normal decay heat removal path is through the counterflow tie tubes. The second, independent, heat removal path is provided by pulsing hydrogen through the reactor.

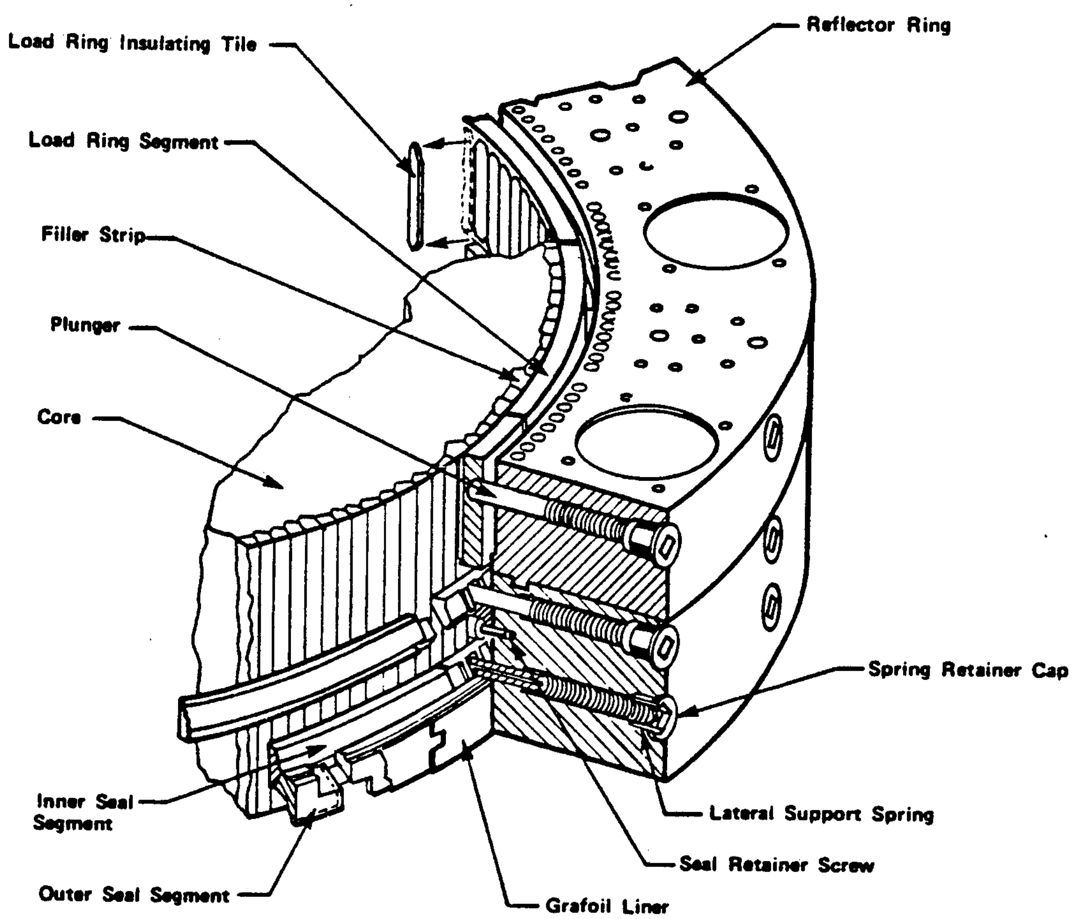
The core lateral support system, shown in detail in Figure 2-5, provides the following functions:

- Reduces the radial heat loss from the core and removes this heat
- Provides bundling forces on the core
- Reduces hydrogen leakage into the core

Component	Mass (kg)	Cost (1000$)*
Reactor	2,200	6,100
Shield (external)	700	500
Hydrogen System		
- Tank & Insulation	580	160
- Coolant System/Pump	390	400
Cesium Seed System	40	300
MHD (disk) Generator	2,380	3,580
Magnet System	720	500
Auxiliary Cooling/Heat Rejection	140	300
Effluent Chamber	85	60
Energy Storage System	100	50
Instrumentation/Control	150	800
Misc. Structures	425	400
Estimated Mass Total Power Conversion System	7,910	13,200

*Mid-1987 dollars, but does not include cost of any development engineering support or services or fees.

Figure 2-4. Estimated Reference Power System Dry Mass Distribution and Cost Estimate (Excluding Power Conditioning)



NDR CORE PERIPHERY:The NDR core periphery and lateral support

Figure 2-5. Details of Core Lateral Support System and Reflector

- Allows radial and axial expansion of the core

- Provides electrical isolation from the pressure vessel and exostructure.

The NERVA lateral support system performed all of these functions except isolation during full power/temperature operation and provided the core support during simulated launch (dynamic and vibration) loads. This same lateral support design will be used in the NDR disk MHD power system with electrical insulation between the two load transfer points (lateral and axial) with the pressure vessel exostructure.

Since equipment experience exists in manufacturing reactors (20 reactors were built during the NERVA/Rover program) some estimates of the expected reactor cost is possible. An update of NRX-A6 type reactor costs to mid-1986 dollars results in a total assembled cost of $7,535,000. For minimal cost with a "throw-away" single mission approach, the reactor components and assembly could be designed for lower radiation dose and higher design stress. A lower requirement for internal shielding and significantly fewer fuel elements (assuming most would be acceptable and allow 15 to 20% for contingency) would be needed. On this basis, and with cost break benefits of a larger number of units to be procured, the reactor subsystem cost of hardware estimate is $3,600,000 with $2,500,000 for assembly and delivery; a unit cost of 6.1 million 1987 dollars, a reasonable goal. This could be less with a graphite and Be reflector configuration.

2.4 Shielding

Both internal and external shielding have been identified for the attenuation of neutron fluence and gamma dose at the payload. The NDR shield design places the gamma shielding ($YH_{1.75}$) within the reactor pressure vessel. This material (Yttrium hydride) is an excellent neutron (as well as gamma) shield material, and, for the design basis damage criteria, no other shield is necessary. The alternate damage criteria are much more restrictive than the design basis criteria, and additional gamma and neutron shielding is required. Additional neutron shielding is provided for outside of the pressure vessel. ZrH_x has been selected for the shielding material due to its ability to meet these requirements and more extensive design understanding.

Although the shielding requirements are not identified, experience with various sensitive instrumentation and control components suggests some additional shielding may be needed. Allowance for shielding mass is not required for attenuation similar to that for the manrated NERVA, based on locating the shielding between the reactor and platform. Some shielding of the aluminium magnet windings, utilizing both structure and a lead cone, is included. The attenuation of radiation dose for both magnet and platform has been provided for in a 700 kg allowance for external shielding.

2.5 Hyperconducting Magnet

The double solenoid aluminum coils of this concept (depicted in Figure 2-6) use hyperconductivity conductor technology.

Conceptual magnet design parameters are:

Field Strength	4 Tesla
Mean Radius	0.52 M
Power Required	35 kW
Stored Energy	6.5 MJ
Ampere Turns	4×10^6 AT
Separation Loading	5000 kN
Mass	720 kg

Recently, high purity (99.9999%) aluminum conductors have been produced with the potential to significantly reduce the mass of systems where liquid hydrogen is available for cooling. A small fraction of the coolant flows through the magnet and is kept in a saturation temperature state by

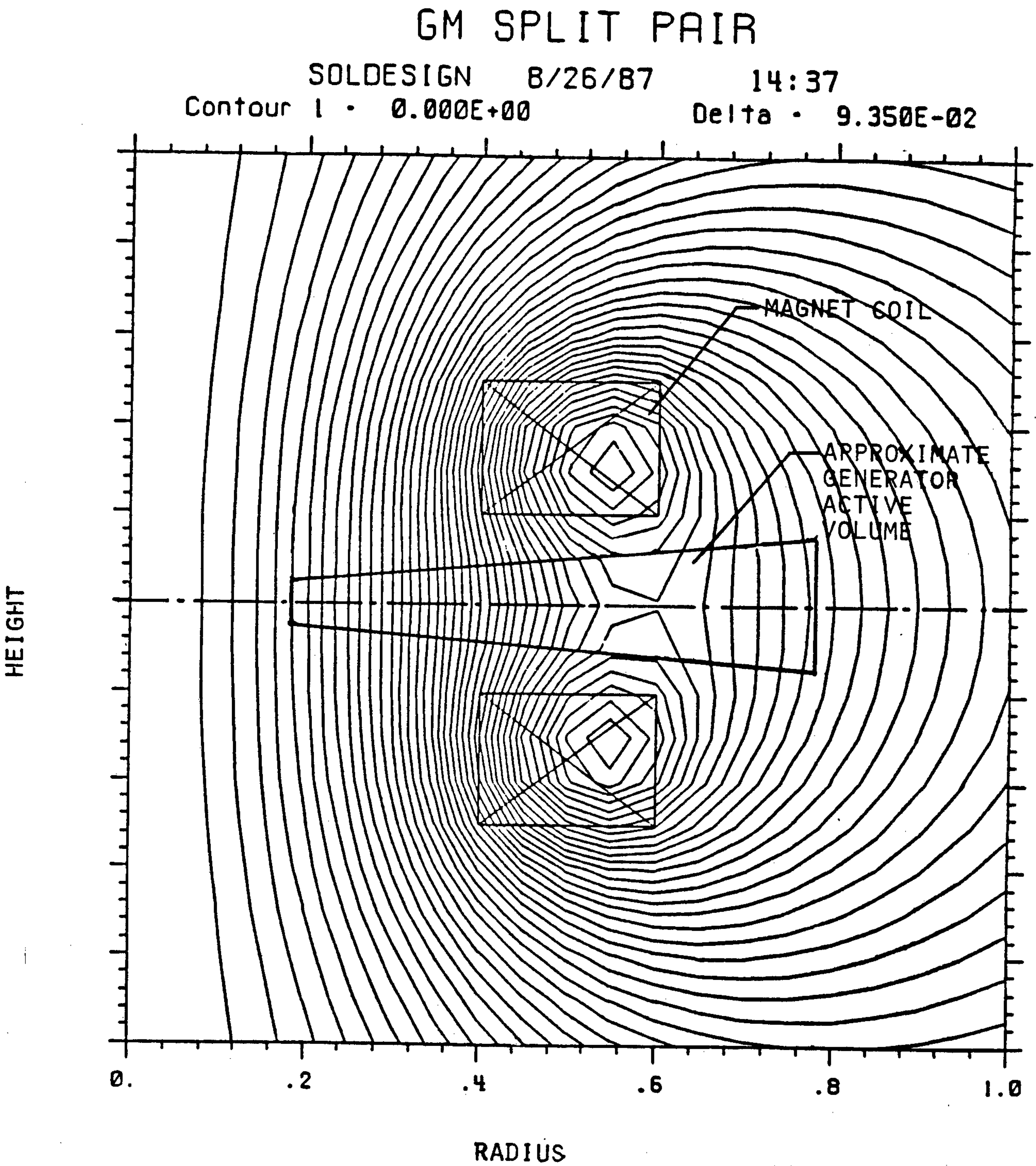


Figure 2-6. Baseline Magnet Flux Contours

expansion. The winding concept is similar to the pancake solenoid superconducting design. The magnet coils are designed so that the heat generation per unit volume is kept to a value that can be cooled by conduction/convection.

High purity aluminum is structure sensitive and therefore increases its resistivity with cold work. Thus, the support of the high purity material is a primary consideration in its application. The approach adopted in this study has been to surround the high purity metal with a structural material that supports and unloads the high purity metal. Conductors made by the Westinghouse Research Center under a USAF Contract have a core of high purity aluminum extruded inside of an Al-Fe-Ce sheath. The advantage of this arrangement is that the structural material is located where it is most efficient in load carrying and protecting the high purity core.

In designing the hyperconducting magnet, all of the coolant is expelled to vacuum, eliminating the need for any pumps. Because the magnet mass is inversely proportional to the hydrogen flow rate for an optimized design, various trade-offs may be carried out in Task 2 to better match the coil mass to the required hydrogen mass. Cost estimates were made based upon experience with conventional solenoid magnets and hyperconducting aluminum coil cost anticipated from materials and cryogenic system experience. The approximate cost of the two cryogenically cooled one meter diameter magnets (split solenoid) is estimated at $0.5M.

2.6 Disk MHD Generator

The reference nuclear disk MHD conversion subsystem configuration, its major functional elements and overall layout dimensions are summarized in Figure 2-2. The key features that are provided by this conceptual generator design configuration are:

- simple compact split solenoid magnet
- few electrodes (three pairs)

- recuperative cooling of structure and electrical conductors

- cancellation of internal swirl forces and radial flow forces (with use of third loading in reversed field of radial outflow beyond magnet and return inflow to axial flow into the effluent control system)

- essentially no net thrust at any condition of operation

- attractive power scaling $(P)^{0.5}$

- Plasma entrance open-circuited volume for full non-equilibrium ionization

- Power to mass ratio of over 40 kW/kg at 100 MW_e

A layout of the key design features of the disk and its configuration are shown in Figure 2-7. Preliminary estimates of dimensions and construction approach are provided as defined for assessing the mass and cost of the generator.

Although considered a viable concept, improvements and alternative design approaches exist that provide options for the preliminary design effort in Task 2. However, for the Task 1 purpose of assessing the system concept, this effort was limited to the definition of a feasible approach without conduction of design trade-offs.

The disk MHD generator flow path radius and height dimensions and operating conditions are summarized in Figure 2-8, and mass and cost estimates have been based upon these dimensions and the operating conditions presented in Figure 2-3.

MATERIAL SELECTIONS

Suitable materials have been identified for conducting conceptual design assessments of the NDR disk MHD power system components. A summary of these

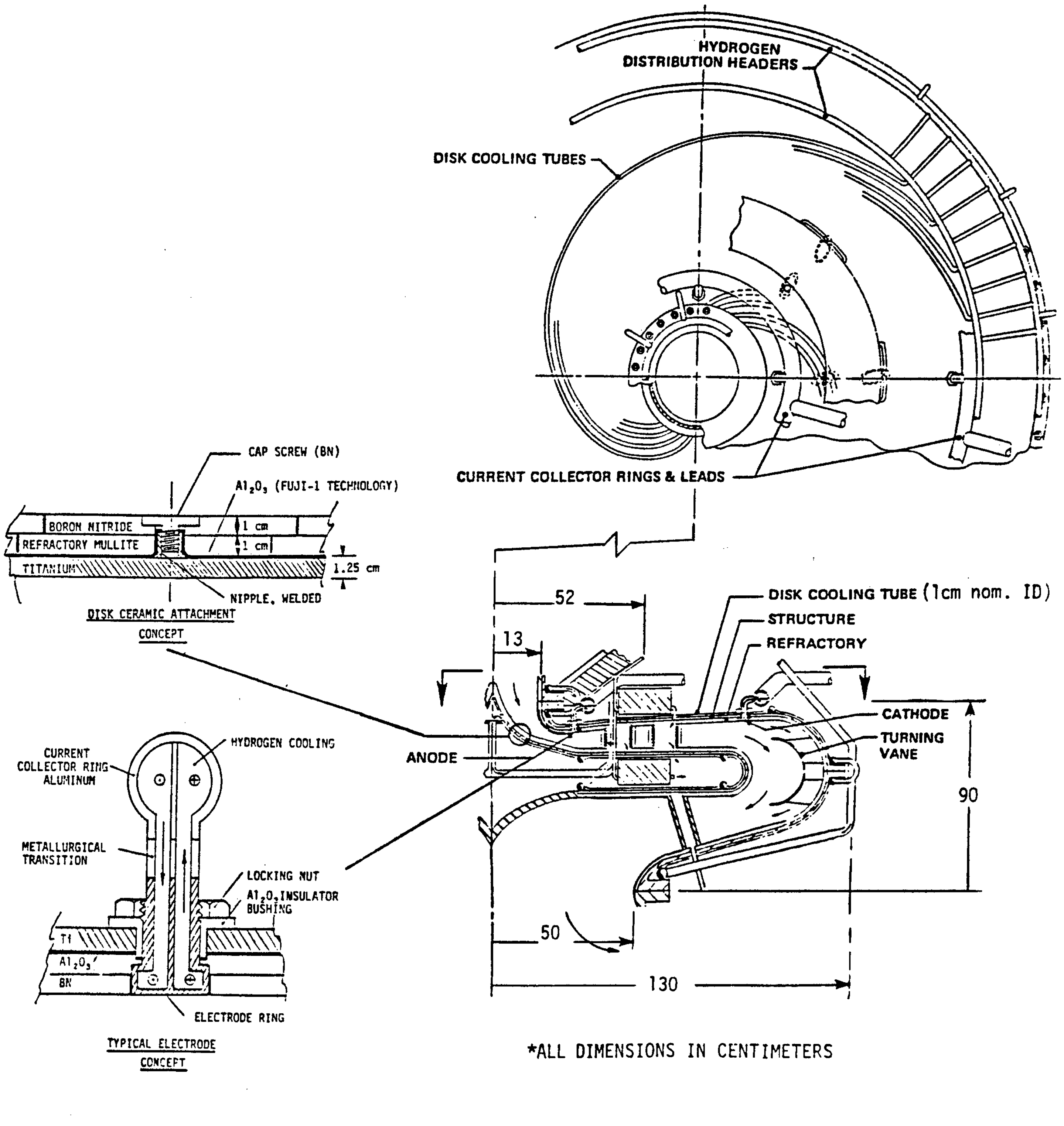


Figure 2-7. Layout and Overall Dimensions of the Disk MHD Generator

MHD SYSTEM ... PERFORMANCE ANALYSIS DATA

DISKSUM TEST

CHANNEL ....

TYPE	DISK	
DIMENSIONS		
INLET - RADIUS,HEIGHT (M)	0.18294	, 4.12118E-02
OUTLET - RADIUS,HEIGHT (M)	0.79786	, 0.17934
MEAN RADIUS (M)	0.61492	
MASS (KG)		
HOUS. & INT. STRUCTURE (KG)	1157.9	
INSULATION (KG)	913.08	
COOLING TUBES & STRUCT (KG)	284.21	
ELECTRODES & CONDUCTORS (KG)	59.401	
TOTAL DISK MASS (KG)	2414.5	
COST ($1000)	3638.1	
NUMBER OF ELECTRODE PAIRS	3.0000	
ENTHALPY EXTRACTION (PCT)	0.00000	
OVERALL (TURBINE) EFFICIENCY (PCT)	0.00000	
INLET CONDITIONS		
PRESSURE (ATM)	1.0587	
TEMPERATURE (DEG K)	1618.0	
MACH NUMBER	2.4000	
VELOCITY (M/S)	7158.8	
FLOW RATE (KG/S)	5.4700	
OUTLET CONDITIONS		
PRESSURE (ATM)	0.11931	
TEMPERATURE (DEG K)	1521.6	
MACH NUMBER	1.0894	
SURFACE TEMPERATURE (DEG K)	1300.0	
HEAT LOSS (MWT)	3.9964	
PEAK ELECTRODE CURRENT DENSITY (A/CM**2)		
MAXIMUM HALL FIELD (KV/M)		
COOLING FLOW INLET		
PRESSURE (ATM)	41.662	
TEMPERATURE (DEG K)	569.00	
QUALITY	1.0000	
FLOW RATE (KG/S)	5.4522	
COOLING FLOW EXIT		
PRESSURE (ATM)	41.662	
TEMPERATURE (DEG K)	579.67	
QUALITY	1.0000	
NUMBER OF CHANNELS	1	
MHD GROSS POWER BEFORE INVERSION (MWE)	111.89	
MHD GROSS POWER AFTER INVERSION (MWE)	107.75	
INVERTER EFFICIENCY (PCT)	98.500	

Figure 2-8. SPA/SUMARY Disk MHD Generator Results

selections is presented in Figure 2-9. Space-proven materials are used where possible and where compatible, however, the hydrogen environment and long space duration of this application require special design consideration for use of titanium to provide the structural functions of the reactor and disk generator pressure containments. A proprietary method is available for applying surface protective coatings that permits the use of this preferred structural material. However, backup materials are available and could be used if the assurances needed are lacking or later kinetic data show any significant risk.

MASS AND COST ESTIMATES

Preliminary mass and cost estimates have been made for the key elements of the nuclear disk MHD space power conversion system. The estimates are based on the reference system configuration and dimensions with selected materials. Cost data were developed from vendor quotes, comparisons with similar procurements, historical data/experience and engineering practices that cover the various items of the component. This cost estimate covers the component/element procurement and assembly cost but not development, engineering support or services that do not enter into direct fabrication/ procurement costs.

The mass and cost of the key disk generator elements have been modeled with algorithms for the SPA/SUMARY code. A printout of a representative calculational result for the reference disk MHD generator is shown in Figure 2-8. The SUMARY system analytical model for costing the power system components was not exercised during the preliminary parametric system studies since this Task 1 effort was concentrated on the disk MHD generator system design conditions and performance impacts.

The mass algorithms are relative to component configuration, material choice and calculated key dimensions. The cost algorithms are based upon estimates made for the reference system and usually are modeled in the form

	Max Temperature Operation (K)	Max Pressure Operation (Atms)	Potential Material
MHD Generator			
Containment Structure	850	16.6/0.25	Ti-6 Al-4V/Surface treated to inhibit H_2 ingress
Thermal/Electrical Insulator	2900	46.6	Boron Nitride Facing plasma/Ref. Mullite/Zironcia adjacent to containment structure.
Coolant Channels	650	36.6	Ti-6 Al-4V/Surface treated to inhibit H_2 ingress
Magnet Supports	2900	0.71	Zirconia clad/W-0.35 HfC
Electrical Leads	567	45.6	Copper reinforced with tungsten filaments (composite)
Hot Channel Reflectors (Diffuser)	1878	2/0.25	Tungsten
Electrodes	2900	16.6	Tungsten
Magnet			
Coils	20	1	High purity aluminum
Structure	20	1	Al-Fe-Ce (Sheath)
Diffuser			
(See MHD Generator)			(Same as channel deflectors)
Effluent Control Chamber			
Containment	1600	<1	Carbon-Carbon Composite, Coated with ZrC

Figure 2-9. Candidate Materials for NDR/MHD Disk Generator System Potential Material

$$COST = A + \beta X_i k^c$$

Where A represents the fixed cost, β is a sensitivity factor (e.g., number of units needed, alternative materials, fabrication method) for the component, X_i is the reference system/component cost basis, k is the scaling parameter (usually related to ratios of mass, power, thermal load, etc.) for the components, and c is the observed scaling exponent.

As discussed in the parametric studies section of the Task 1 report, there are constraints on the combination of design variables for the parameters required for the MHD disk to operate at high performance in a stable condition. However, the selection of the combination of the variables within these key parameters leaves considerable range for both engineering design and power output trade-offs.

Since high voltage is desired for minimizing the power conditioning system size and mass, and higher voltage can be attained in the disk generator with design conditions off optimal for power density, some shift from the peak power condition is desired. Review of the SPA results for various design conditions studied during Task 1 indicate that increasing the Mach Number and magnetic field with corresponding increase in inlet stagnation pressure would both improve energy extraction and provide this desired higher voltage.

The disk electrical design is quite flexible and with the results of power conditioning assessments just concluded, the reference design should be revisited to improve performance, reduce power conditioning and provide a better space system.

The disk geometry shown in Figure 2-7 has been defined from the SPA disk MHD model printout for the reference case. The disk dimensional data for the flow path and magnet for this reference case are tabulated in Figure 2-10. The design modification for a 50 percent higher voltage and equivalent performance and would result in the inlet radius increasing only slightly (~ 0.2 m maximum), and the outer radius would extend only an additional 0.2 m (to 0.90 m).

FIRST LOAD (Electrode Pair)	
Inlet Radius	18
Flow Path Height	4.4
Radial Length	6
Outlet Radius	24
Outlet Height	6.3
SECOND LOAD (Electrode Pair)	
Inlet Radius	25
Flow Path Height	6.3
Active Radial Length	7
Outlet Radius	44
Outlet Height	14.7
THIRD LOAD (Electrode Pair)	
Inlet Radius	55
Flow Path Height	11
Radial Length	23
Outlet Radius	78
Outlet Height	15.4
MAGNET MEAN RADIUS	52
Coil Gap	25
OUTER DISK RADIUS	130
DISK HEIGHT (Incl. Flanges)	90

Figure 2-10. Summary of Key Generator Dimensions (cm)

3.0 NDR/MHD POWER SYSTEM INTEGRATION ISSUES

INTRODUCTION

The space-based multimegawatt MHD power system under study by Westinghouse employs an MHD generator in a disk configuration for energy conversion and a NERVA Derivative Reactor (NDR) as the heat source. This power system must be compatible with all the environmental conditions it will encounter and all interfacing systems during all phases of the power system life cycle. The purposes of this present discussion are to: (1) summarize the overall power system integration issues, and (2) review several integration issues specific to the proposed NDR/MHD power system.

INTEGRATION REQUIREMENTS

The full scope of environmental and system integration requirements for all life cycle phases of the NDR/MHD power system are summarized in Table 3-1. Compatibility with the environments and interfacing systems requires structural, mechanical and electrical integration and control of interactive effects between the power system and the other systems. The following definitions are applicable to Table 3-1 requirements:

- The natural environment must be addressed by design, protective measures, and procedures for normal conditions and in the event of malfunctions, launch aborts, etc.

- The threat environment is defined by national security procedures and classified on-orbit requirements.

- Terrestrial facilities include those required for the design through launch phases. Other terrestrial facilities include those that may be used for command and control of on-orbit operations.

TABLE 3-1. ENVIRONMENTAL AND SYSTEM INTEGRATION REQUIREMENTS FOR THE NDR/MHD DISK MMW POWER SYSTEM

	ENVIRONMENTS		SYSTEMS				
Life Cycle Phases	Natural	Threat	Terrestrial Facilities	Launch Vehicle	On-Orbit Equip/Vehicles	Weapon System	Space-Craft
<u>Terrestrial:</u>							
Design	X		X	X	X	X	X
Manufacture	X	As Defined By National Security Procedures	X				
Transport	X		X				
Install	X		X	X			
Launch	X		X	X	X		
<u>Orbital:</u>							
Positioning	X		X	X	X		
Assembly	X	As Defined By Classified Requirements	X		X	X	X
Check-Out	X		X		X	X	X
Test	X		X		X	X	X
Operation	X		X		X	X	X
Maintenance	X		X		X	X	X
Disposal	X		X		X	X	X

- Launch vehicles may include the Shuttle (STS), the Advanced Launch System (ALS) or other launch vehicles.

- On-Orbit Equipment and Vehicles may include the Orbital Maneuvering Vehicle (OMV) and other robotic devices, maintenance equipment, or propulsion systems.

- The Weapon System is defined as a generic, tube type neutral particle beam (NPB) for the purposes of the present study.

- The Spacecraft is the complete on-orbit assembly that includes the weapon system, power system, command and control subsystem, and auxiliary subsystems.

Each of the requirements by power system life cycle phase that are indicated in Table 3-1 represent sets of data, specifications, and criteria. Many categories of these requirements are beyond the present MHD power system conceptual design scope or are presently undefined. For this reason, Westinghouse has prepared an initial Requirements Document[(3-1)] as a "living document" that will be upgraded as the MHD Power System Feasibility Assessment Program proceeds. At present, the reference (3-1) document includes requirements for the power system performance and duty cycle, the interface with the weapon system, STS interface criteria, and the on-orbit natural environment.

NDR/MHD POWER SYSTEM CHARACTERISTICS

The NDR/MHD power system is shown schematically in Figure 3-1 and pictorially in Figure 3-2. A dedicated liquid hydrogen supply is used to provide the system working fluid, although the SDI mission supply on-board the space craft

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(3-1) WAESD-TR-88-0002, Conceptual Design of a Space-Based Multimegawatt MHD Power System, Task 1 Topical Report Volume II: Requirement Document January 1988

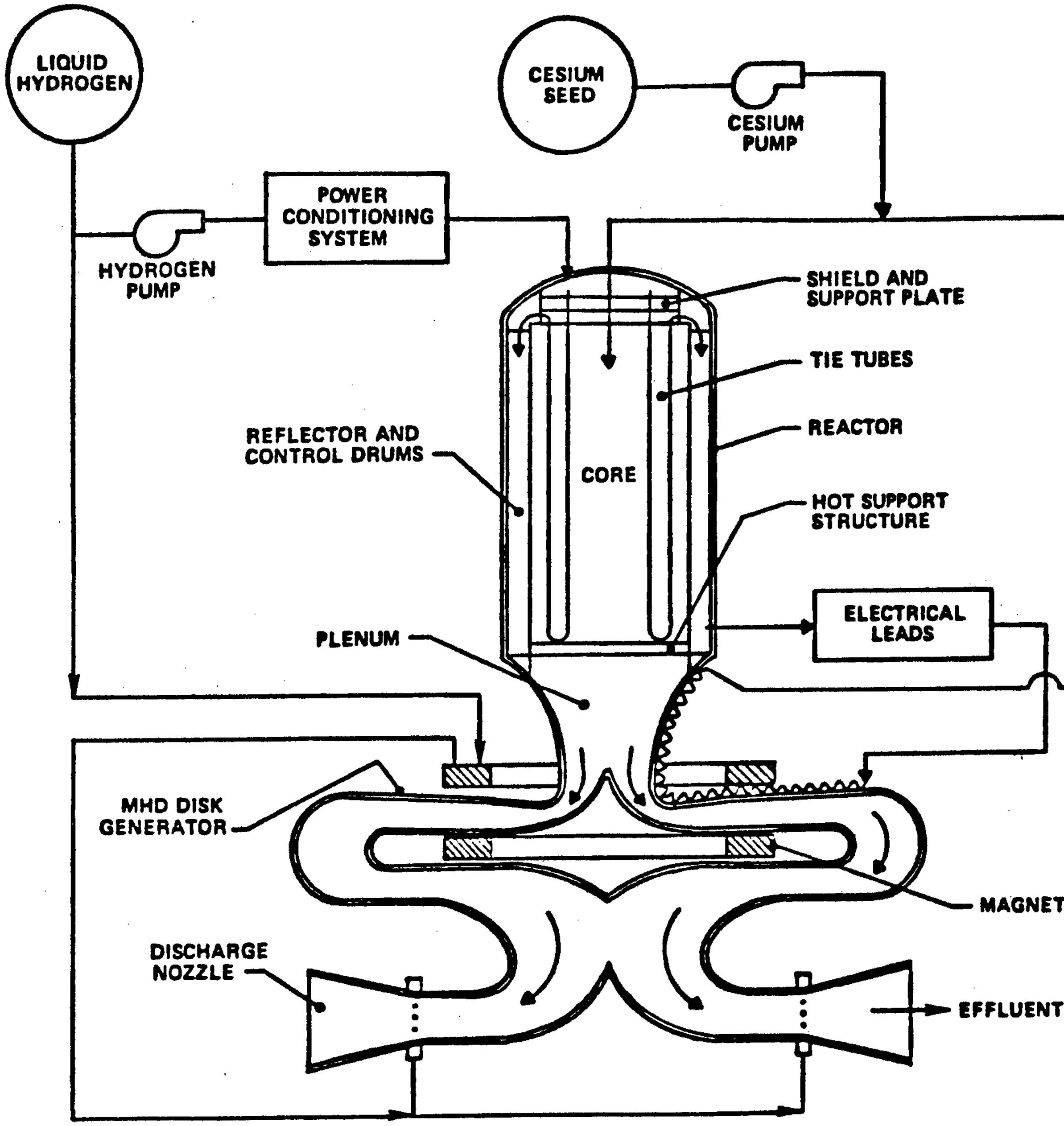

Figure 3-1. Power System Schematic

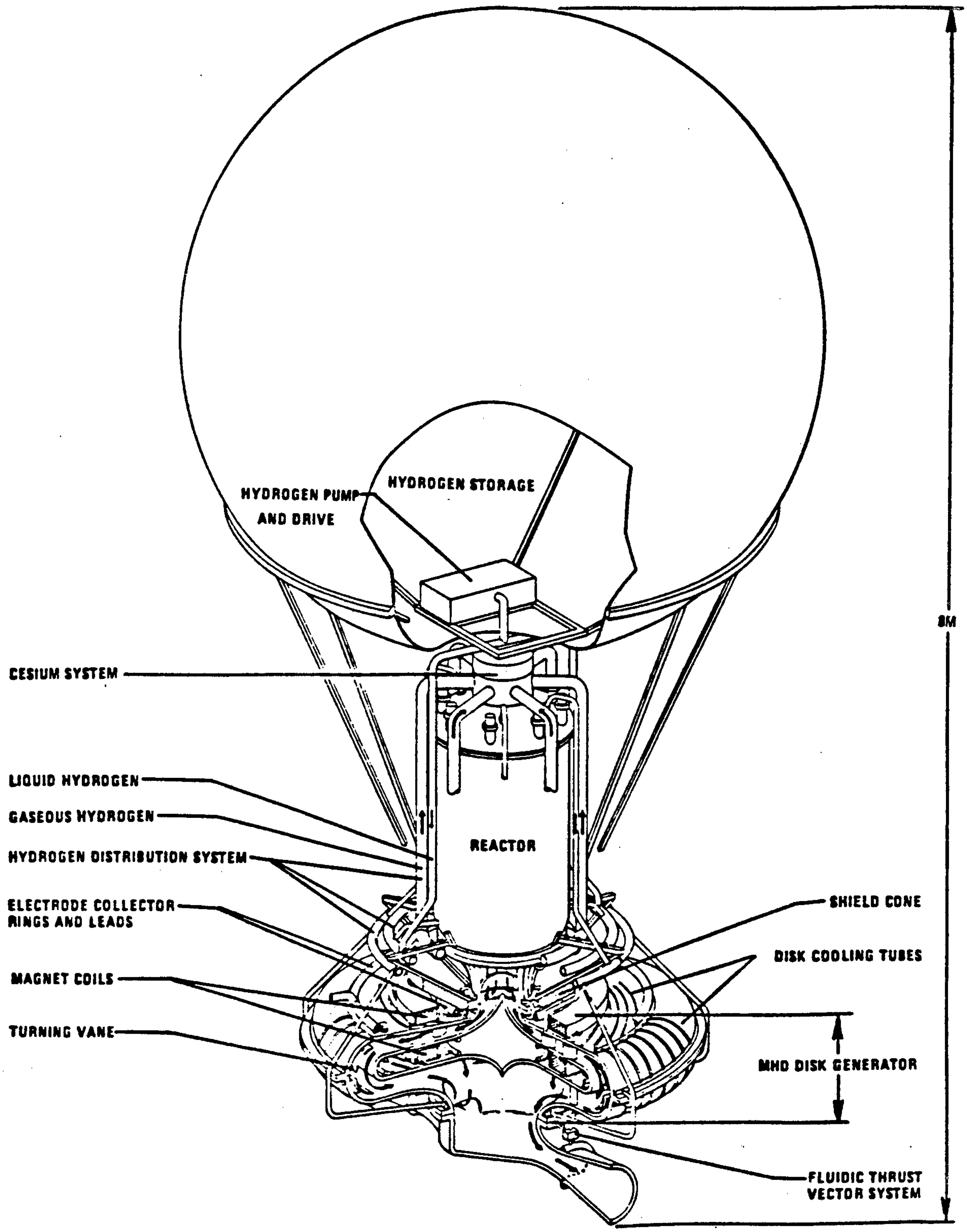

Figure 3-2. MHD Power System Concept

could be used as an option. Sufficient hydrogen supply (and cesium seed for MHD ionization) is provided for 500 seconds of burst power at 100 MW_e. Pertinent system flow rates are as follows:

Reactor/MHD Hydrogen	=	5.452 kg/sec
Reactor/MHD Cesium (0.33% by wt.)	=	0.018 kg/sec
Magnet Cooling	=	0.078 kg/sec
Total Effluent Flow	=	5.548 kg/sec

The effluent exits the open cycle system through two opposing nozzles to balance thrust forces. The magnet cooling hydrogen stream is used for fluidic control to negate any thrust imbalance and is added to the Reactor/MHD disk stream for a total effluent flow of 5.548 kg/s.

System performance is as follows:

Gross DC Power at MHD Terminals	=	108.4 MW_e
Auxiliary Power and System Losses	=	- 7.6 MW_e
Net Power to NPB Load Leads	=	100.8 MW_e
Reactor Thermal Input	=	261.0 MW_t
MHD Energy Extraction	=	42%

The mass (in kilograms) of the NDR/MHD Power System (including the LH_2 and cesium inventory) is:

Reactor & Internal Shielding	=	2,200 kg
Shielding (Magnet & Electronics)	=	700 kg
LH_2 (Initial Mass = 5680 kg), Container & Insulation	=	6,260 kg
Magnet	=	720 kg
MHD Generator Subsystem	=	2,460 kg
Seed (Initial Mass = 10 kg), Container & Pump	=	40 kg
Associated Piping, Structure, Misc. Components	=	1,220 kg
Total Mass (exclusive of Power Conditioning)	=	13,600 kg

A more detailed description of the NDR/MHD power system is presented in the conceptual design topical report.(3-2)

NDR/MHD POWER SYSTEM INTERACTIVE EFFECTS

The requirement categories of Table 3-1 are, to a large extent, generic to all types of space-based multimegawatt power systems. For this discussion, however, we will consider only open cycle burst power systems and compare the NDR/MHD power system with other open cycle systems designed for the same power level and burst duration. The objective is an assessment of selected interactive effects of the NDR/MHD power system and competing systems.

Table 3-2 is a listing of NDR/MHD power system components and features with the potential for causing interactive effects on the weapon system or space platform. Effects originating within the weapon system or other parts of the space platform with the potential for impacting power system design and operation must also be considered. For this evaluation, however, we will focus on effects originating within the NDR/MHD power system. The specific effects to be considered are: the effluent volume and constituents, the effluent thrust, and the dynamic effects on the space platform.

Power System Comparisons

The NDR/MHD Disk Power System is configured such that the effluent is ejected through two opposing nozzles to balance thrust forces. With this configuration, the ejection nozzles in the effluent control subsystem can be designed to operate at specific exit conditions. For example, it may be desirable to maximize the effluent jet velocity to disperse the effluent cloud away from the space platform. But there is a thrust trade-off as shown in Table 3-3, and any uncontrolled imbalance in thrust between the two ejection nozzles will tend to be larger at higher Mach numbers. However, in this

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(3-2) WAESD-TR-88-0002, Conceptual Design of a Space-Based Multimegawatt MHD Power System, Task 1 Topical Report Volume I: Technical Discussion (Draft), January 1988

TABLE 3-2. NDR/MHD POWER SYSTEM - SOURCES OF PRIMARY INTERACTIVE EFFECTS

Power System Feature or Component	Characteristics Causing Potential Interactions	Primarly Interactive Effects					
		Vibration Mech. Noise	Thrust or Torque	Electrical Noise	Thermal Interactions	Plasma Interactions	Power Interactions
Liquid H_2 Storage and Supply (Incl. Tank, Pump and Motor, Refrigeration System, Radiator and Piping)	• Sloshing of LH_2		X				
	• Elec. Motor Oper.	X	X	X			X
	• Pump Operation	X	X				
	• LH_2 Flow	X	X				
	• Refrig. Sys. Oper.	X		X			X
	• Heat Rejection				X		
Cesium Storage and Supply (Incl. Pump, Heater, Tank, and Piping)	• Sloshing of Liquid		X				
	• Elec. Motor Oper.	X	X	X			X
	• Pump Operation	X	X				
	• Heater Operation			X	X		X
	• Cesium Flow	X	X				
Electrical Leads	• Magnetic Field		X	X		X	
	• LH_2 Coolant Flow	X	X				
	• Heat Rejection				X		
	• Electrical Transmission			X		X	X
Reactor	• Radiation (Nuclear)				X	X	
	• Radiation (Thermal)				X		
	• Control Drum Oper.	X	X	X			X
	• Liquid/Gas Flow	X	X				
MHD Disk Magnet	• Magnetic Field		X			X	X
	• Current Flow		X	X		X	
	• Coolant Flow	X	X		X		
	• Energy Storage			X			X

TABLE 3-2. NDR/MHD POWER SYSTEM - SOURCES OF PRIMARY INTERACTIVE EFFECTS (Continued)

Power System Feature or Component	Characteristics Causing Potential Interactions	Primarly Interactive Effects					
		Vibration Mech. Noise	Thrust or Torque	Electrical Noise	Thermal Interactions	Plasma Interactions	Power Interactions
MHD Disk Generator	• Ionization			X		X	X
	• Energy Extraction	X	X	X			X
	• Swirl Flow	X	X				
	• Reverse Flow	X	X				
	• Coolant Flow	X	X		X		
Effluent Control Subsystem	• Gas Flow	X	X			X	
	• Coolant Injection	X	X				
	• Fluidic Control Oper	X					
	• Effluent Ejection	X	X	X	X	X	
	• Effluent Cloud			X	X	X	
Power Conditioning Subsystem	• DC/AC/DC Conversion			X			X
	• Coolant Flow	X	X		X		
	• Magnetic Fields					X	
	• Electrical Fields					X	
I&C Subsystem	• Electrical Processes			X		X	X
	• Mechanical Processes	X	X				

TABLE 3-3. NDR/MHD POWER SYSTEM EFFLUENT NOZZLE EJECTION PARAMETERS

Mach Number	=	1.0	1.5	2.0
Jet Velocity, m/s	=	2940	4050	4880
Thrust Per Nozzle, N	=	8150	11,230	13,540

- -

NOTES:

Total Mass Fow = 5.548 kg/s

Mass Flow Per Nozzle = 2.774 kg/s

The total mass flow includes the hydrogen and cesium disk MHD working fluid plus the magnet cooling hydrogen injected through the fluidic thrust control subsystem.

One Newton (N) = 1 kg-m/s^2 = 0.225 lb evaluation we have selected a Mach number of 1.5 for the power system comparisons. Three nominal 100 MW_e open cycle burst power systems were compared. They were: the NDR/MHD Disk power system, an NDR/MHD linear channel power system, and a liquid hydrogen/liquid oxygen combustion turbo-alternator power system. The MHD linear channel characteristics are unclassified Westinghouse estimates. The combustion turbo-alternator characteristics are from unclassified LANL data. Characteristic data for the three systems is presented in Table 3-4. It was assumed that the open cycle effluent was ejected from two opposing nozzles for all three systems.

Effluent Thrust

Figure 3-3 summarizes the effluent thrust data from Table 3-4 for the three power systems. The nozzle exit velocity is the same for both MHD systems but considerably lower for the combustion turbo-alternator which has a much lower total exit temperature (estimated at 530 K). The total thrust, as represented by a two percent imbalance in Figure 3-3, is the lowest for the NDR/MHD disk system because it has the highest energy extraction per kilogram of effluent flow (~20 MJ/kg). The jet velocity and thrust produced by the combustion alternator system is probably in the range of other combustion systems, including combustion driven MHD power systems, although they may have different effluent constituents.

Effluent Quantity and Constituents

Figure 3-4 shows the total effluent produced by each open cycle power system for a 100 second power burst at 100 MW_e. A logarithmic scale is used for the ordinate of Figure 3-4, thus illustrating the fact that the condensible cesium concentration by weight in the effluent cloud from the NDR/MHD disk system is orders of magnitude lower than the condensibles from the other systems. Figure 3-4 considers only the effluent from the power systems and assumes the power systems have dedicated working fluid supplies. Figure 3-5 compares the systems with the dedicated working fluid supplies and with the option of using the weapon system thermal stabilization coolant as the power

TABLE 3-4. OPEN CYCLE BURST POWER SYSTEM EFFLUENT CHARACTERISTICS

POWER SYSTEM TYPE	NDR/MHD DISK	NDR/MHD[1] CHANNEL	COMBUSTION[2] TURBO-ALTERNATOR
Net Burst Power (MW_e)	100	100	100
Total Eff. Flow Rate (kg/s)	5.548	18.32	21.1
Power/Flow (MW_e-s/kg)	19.82	6.0	5.19
Effluent Constituents:			
Hydrogen (kg/s)	5.53	15.58	6.4
H_2O (kg/s)	N/A	N/A	14.7
Cesium (kg/s)	0.018	2.74	N/A
Ejection Parameters:			
Mach Number	1.5	1.5	1.5
Jet Velocity (m/s)	4050	4050	1347
Thrust per Nozzle (N)	11.2	37.1	14.2
Specific Impulse (s)	413	413	137
2% Thrust Imbalance (N)	0.22	0.74	0.38

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(1) Unclassified Westinghouse estimates.

(2) Based on unclassified LANL data.

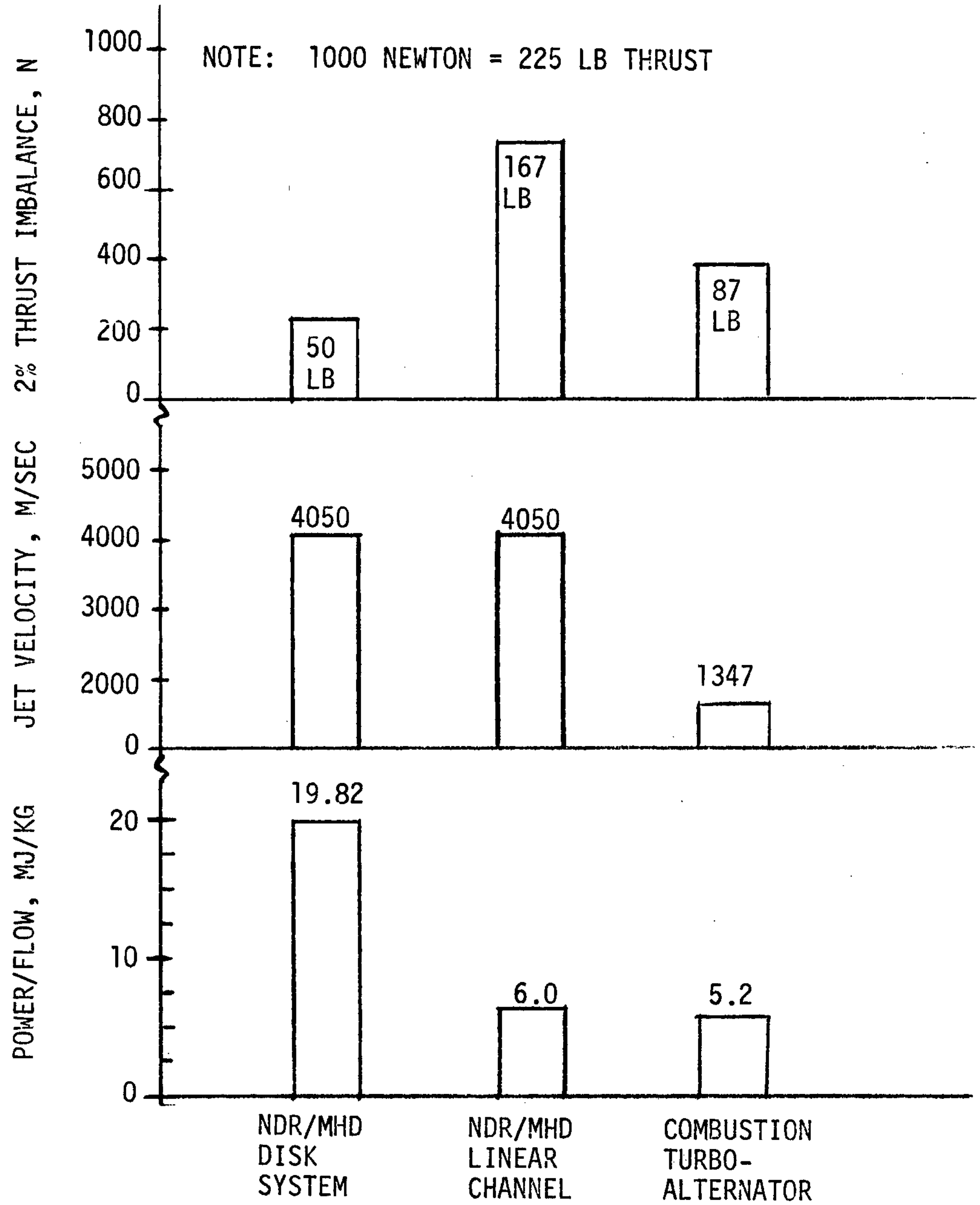


Figure 3-3. Flow Energy Extraction, Effluent Jet Velocity and Effluent Thrust Parameters for 100 MW_e Open Cycle Burst Power Systems

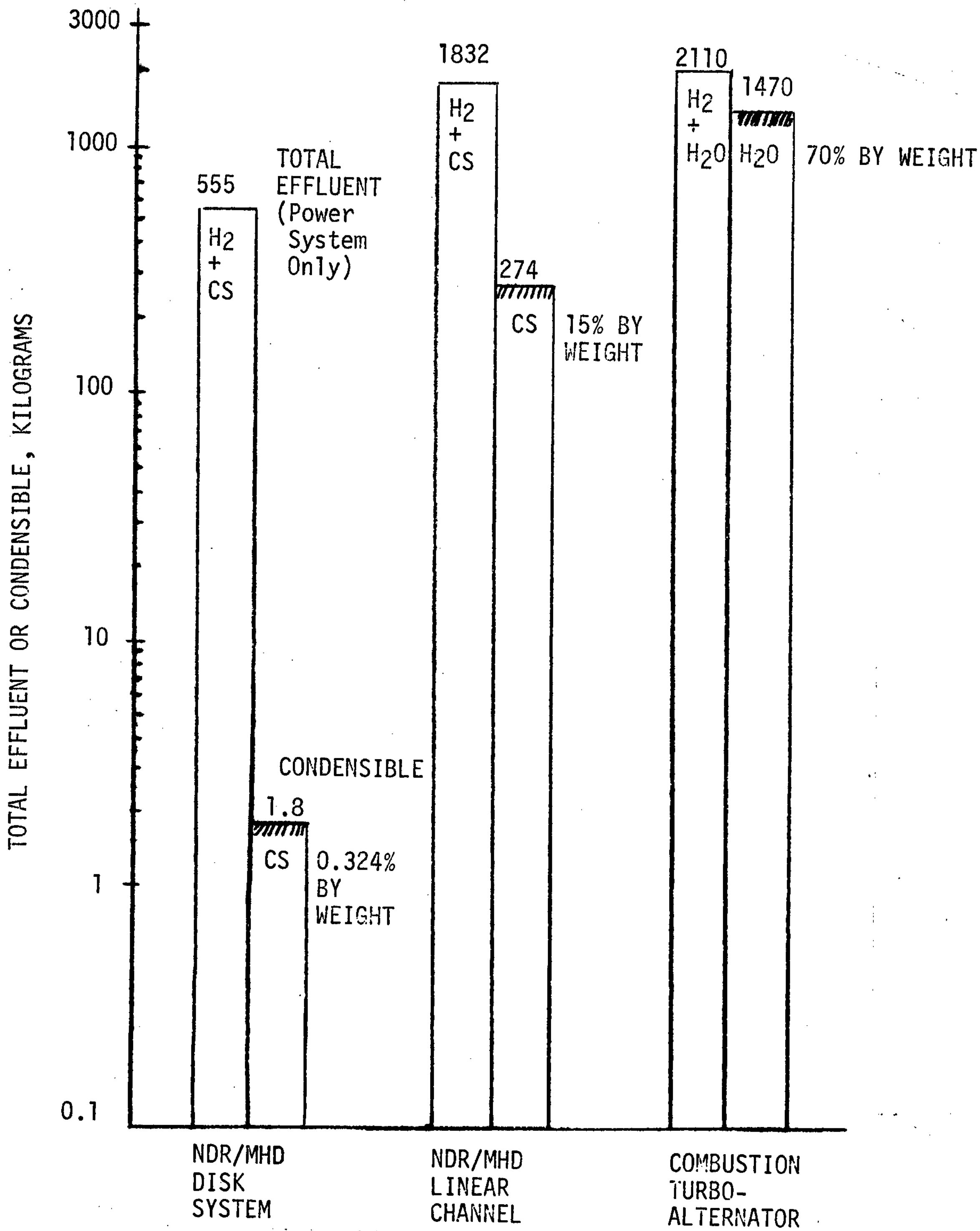


Figure 3-4. Power System Effluent and Condensibles for 100 MW_e Power Systems Operating for a 100 Second Open Cycle Burst

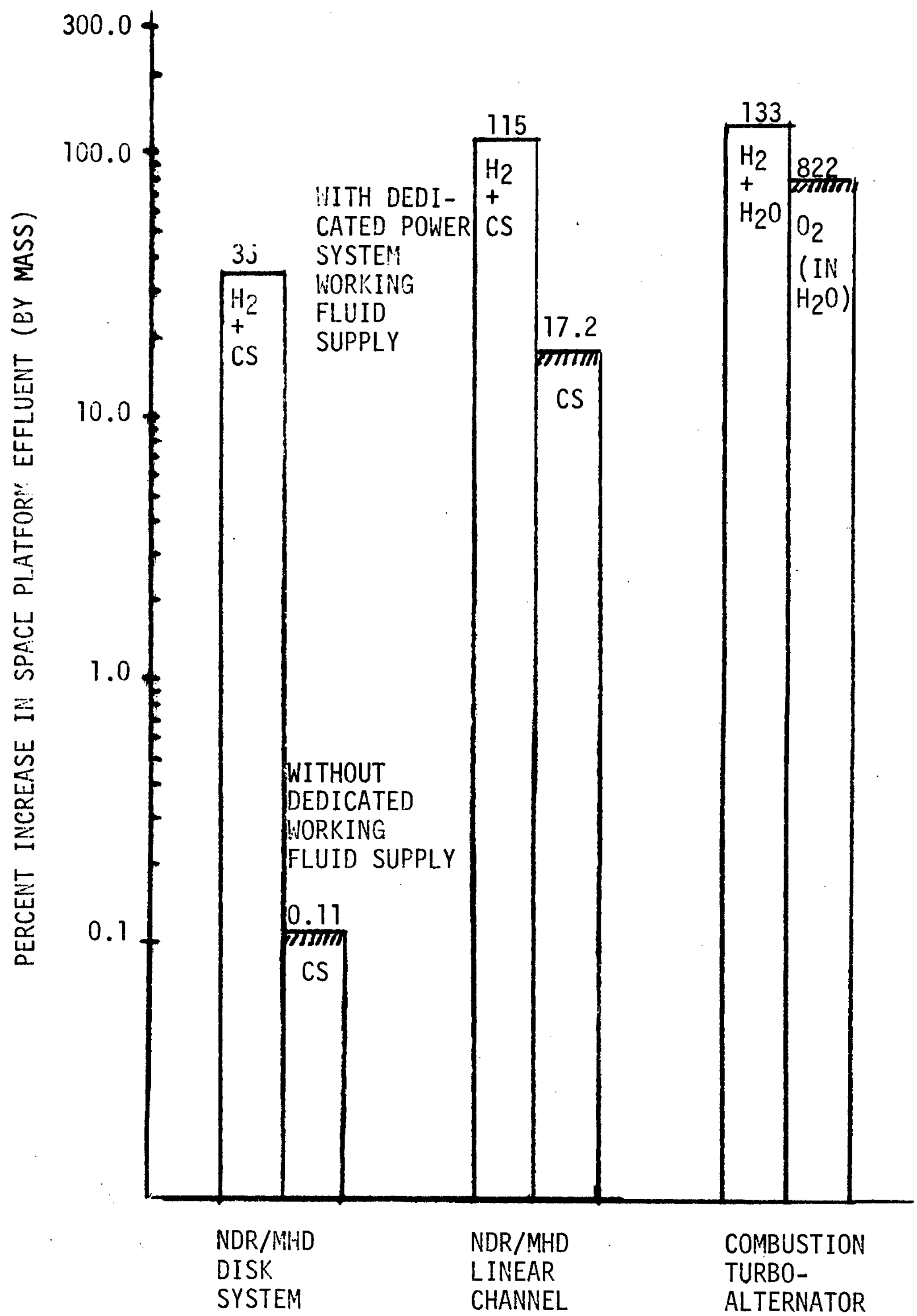


Figure 3-5. Percent Increase (By Weight) in Space Platform Effluent With and Without Dedicated Power System Working Fluid Supply (100 MW_e Open Cycle Burst Power)

system working fluid. When the latter option is used and the power system is integrated with the weapon coolant, the total increase in effluent cloud mass due to operation of the NDR/MHD disk is only 0.11 percent. Table 3-5 summarizes information from both Figures 3-4 and 3-5.

From Table 3-5, it can be seen that the percentage of cesium in the total space platform effluent cloud mass is 0.1 percent or less for the NDR/MHD disk system in both the integrated and non-integrated cases. A condensible concentration of such a small magnitude should not adversely impact space platform functions unless it selectively condenses in specific locations. Further study in this area is needed, but if necessary, the MHD disk effluent control subsystem can be designed to remove cesium from the effluent prior to nozzle ejection. One option is to provide hydrogen cooling of the effluent subsystem structure in order to condense out the cesium before the effluent is ejected. Since the cooling arrangement for the NDR/MHD disk power system is regenerative, there will be only a minor system efficiency penalty when this design option is used.

Table 3-5 also shows that, from the condensible standpoint, the NDR/MHD disk power system effluent is very benign compared to the MHD linear channel and combustion turbo-alternator power systems. The large amount of water in the combustion turbo-alternator has the potential for serious adverse effects. It is recognized that the other combustion processes that do not produce H_2O or CO_2 can be used to drive a turbine or MHD energy convertors. However, any combustion process will add significantly more mass to the total space platform effluent cloud than the NDR/MHD disk power system, even if the combustion process utilizes "free" hydrogen from the weapon system.

Dynamic Effects

The NDR/MHD disk power system, in a configuration with a power conditioning system and a Neutral Particle Beam weapon, was modeled as a rigid body in order to investigate the effect of effluent thrust forces. The configuration is illustrated in Figure 3-6, and the component dimensions and masses are listed in Tables 3-6, -7 and -8.

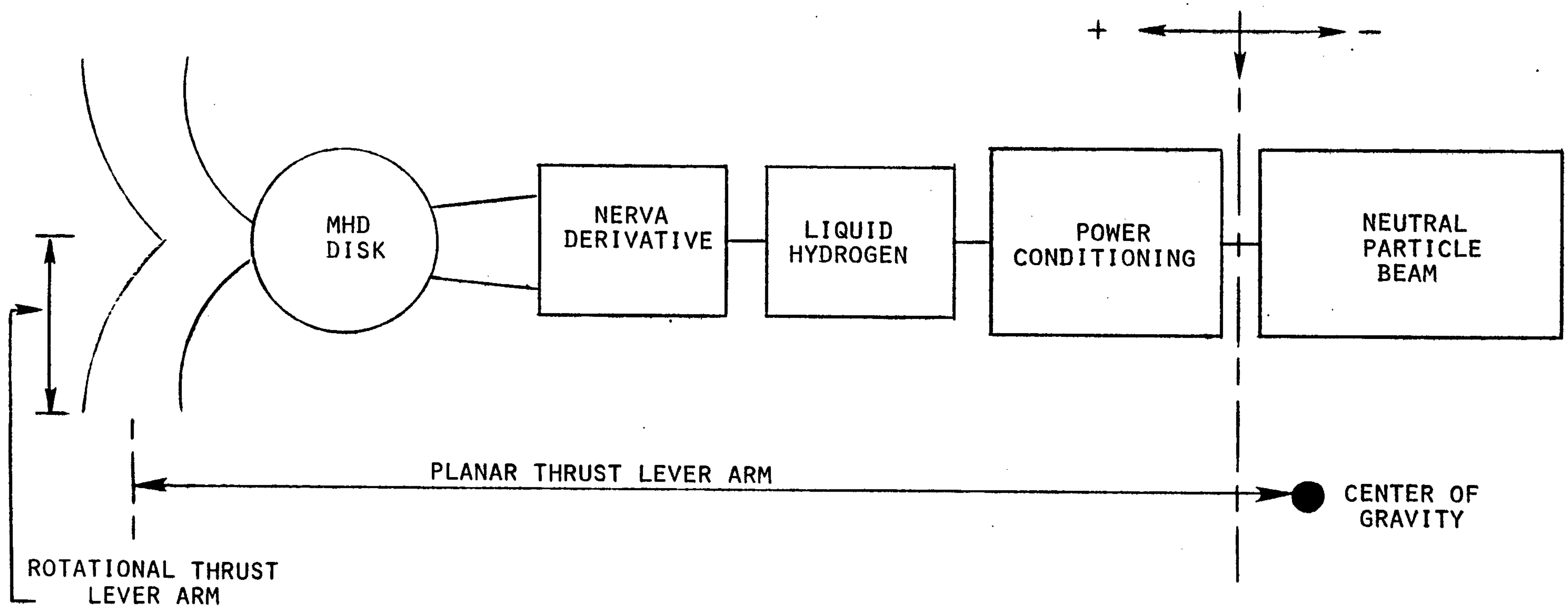
TABLE 3-5. TOTAL SPACE PLATFORM EFFLUENT QUANTITIES WITH AND WITHOUT DEDICATED POWER SYSTEM WORKING FLUID SUPPLIES

Non-Integrated Systems/Dedicated Supply (100 s Burst)

Power System Type	=	NDR/MHD Disk	NDR/MHD Channel	Combustion Turbo-alternator
Total Effluent Mass, kg	=	2145	3422	3700
Percent Increase in Effluent Mass Relative to Weapon System Effluent Mass	=	35	115	133
Condensible Mass in Total Effluent Cloud, kg	=	1.8 (Cs)	274 (Cs)	1470 (H_2O)
Percent Condensible in Total Effluent Cloud	=	0.084 (Cs)	8.0 (Cs)	39.7 (H_2O)

Integrated Systems Using Weapon System Coolant (100 s Burst)

Power System Type	=	NDR/MHD Disk	NDR/MHD Channel	Combustion Turbo-alternator
Total Effluent Mass, kg	=	1592	1864	2897
Percent Increase in Total Effluent Mass Due to Power System Operation	=	0.11	17.2	82.2
Condensible Mass in Total Effluent Cloud, kg	=	1.8 (Cs)	274 (Cs)	1470 (H_2O)
Percent Condensible in Total Effluent Cloud	=	0.11 (Cs)	14.7 (Cs)	50.7 (H_2O)



NOTE: DIMENSIONS AND MASSES ARE GIVEN IN TABLES 3-6, -7 AND -8.

Figure 3-6. NDR/MHD Disk Power System Rigid Body Dynamic Model

TABLE 3-6. INERTIA AND C/G OF ASSEMBLY - FULL HYD. TANK - NPB MODELLED AS SOLID CYLINDER

Item	Mass Kg	Geometry	Length Meters	Radius Meters	Roll Inertia C/G Kgm-m-m	Pitch Inertia C/G Kgm-m-m	Distance From NPB Meters	First Moment Kgm-m	Mass Times L*L
Power Conditioner	25,300	Solid Cylinder	5.50	2.50	79,063	103,308	2.75	69,575	859,253
Shield	900	Disk	0.00	2.50	2,813	1,406	5.50	4,950	66,220
Hyd. Tank (Full)	6,300	Solid Cylinder	5.50	2.15	14,561	23,162	7.9	17,325	213,964
Reactor	2,200	Solid Cylinder	2.00	0.45	223	845	11.3	19,800	320,918
Generator Disk	2,180	Solid Cylinder	1.00	1.00	1,090	727	12.7	22,890	401,894
Effluent Subsystem	80	Disk	0.7	1	40	23	13.36	908	16,653
NPB	36,000	Solid Cylinder	20.00	4.00	288,000	1,344,000	-10.00	(360,000)	1,725,036
Total Assembly	72,960	Kgm			385,789	1,473,471		(224,552)	3,603,938

Roll Inertia 385,789 Kgm-m-m C.G. = -3.08

Pitch Inertia 5,077,409 Kgm-m-m

Center of Gravity -3.077741 Meters (+ From PC/NPB Interface Towards Generator Disk)
(- From PC/NPB Interface Towards NPB)

TABLE 3-7. INERTIA AND C/G OF ASSEMBLY - (HALF FULL) HYD. TANK - NPB MODELLED AS SOLID CYLINDER

Item	Mass Kg	Geometry	Length Meters	Radius Meters	Roll Inertia C/G Kgm-m-m	Pitch Inertia C/G Kgm-m-m	Distance From NPB Meters	First Moment Kgm-m	Mass Times L*L
Power Conditioner	25,300	Solid Cylinder	5.50	2.50	79,063	103,308	2.75	69,575	931,859
Shield	900	Disk	0.00	2.50	2,813	1,406	5.50	4,950	69,997
Hyd. Tank Half	3,400	Solid Cylinder	5.50	2.15	7,858	12,500	7.9	9,350	125,230
Reactor	2,200	Solid Cylinder	2.00	0.45	223	845	11.3	19,800	333,865
Generator Disk	2,180	Solid Cylinder	1.00	1.00	1,090	727	12.7	22,890	416,301
Effluent Subsystem	80	Disk	0.7	1	40	23	13.6	908	17,214
NPB	36,000	Solid Cylinder	20.00	4.00	288,000	1,344,000	-10.00	(360,000)	1,606,902
Total Assembly	70,060	Kgm			379,086	1,462,809		(232,527)	3,501,370

Roll Inertia 379,086 Kgm-m-m C.G. = -3.32

Pitch Inertia 4,964,179 Kgm-m-m

Center of Gravity -3.318969 Meters (+ From PC/NPB Interface Towards Generator Disk)
(- From PC/NPB Interface Towards NPB)

TABLE 3-8. INERTIA AND C/G OF ASSEMBLY - DRY HYD. TANK - NPB MODELLED AS SOLID CYLINDER

Item	Mass Kg	Geometry	Length Meters	Radius Meters	Roll Inertia C/G Kgm-m-m	Pitch Inertia C/G Kgm-m-m	Distance From NPB Meters	First Moment Kgm-m	Mass Times L*L
Power Conditioner	25,300	Solid Cylinder	5.50	2.50	79,063	103,308	2.75	69,575	1,010,760
Shield	900	Disk	0.00	2.50	2,813	1,406	5.50	4,950	74,049
Hyd. Tank (Dry)	610	Solid Cylinder	5.50	2.15	1,410	2,243	7.9	1,678	24,370
Reactor	2,200	Solid Cylinder	2.00	0.45	223	845	11.3	19,800	347,648
Generator Disk	2,180	Solid Cylinder	1.00	1.00	1,090	727	12.7	22,890	431,605
Effluent Subsystem	80	Disk	0.7	1	40	23	13.6	908	17,810
NPB	36,000	Solid Cylinder	20.00	4.00	288,000	1,344,000	-10.00	(360,000)	1,488,103
Total Assembly	67,270	Kgm			372,638	1,452,552		(232,527)	3,394,345

Roll Inertia	372,638	Kgm-m-m	C.G. =	-3.57
Pitch Inertia	4,846,897	Kgm-m-m		
Center of Gravity	-3.570677	Meters	(+ From PC/NPB Interface Towards Generator Disk) (- From PC/NPB Interface Towards NPB)	

The system was modeled with the dedicated power system hydrogen tank full, half-full and empty to assess the impacts on roll and pitch inertia and center of gravity location. A two percent thrust imbalance was used to calculate the acceleration values listed in Table 3-9. The acceleration values calculated on this basis are quite low, and a two percent thrust imbalance can easily be counteracted with small positioning thrusters. A fluidic thrust control mechanism to minimize or eliminate thrust differences between the two opposing exit nozzles of the MHD disk system has been proposed. Testing during subsequent tasks of the MHD Feasibility Assessment program is needed to demonstrate the proposed concept capability to control thrust imbalances. In any case, thrust imbalance between the opposing nozzles may not be coincident and can therefore have both planar and rotational moments. A three dimensional thrust control mechanism is required and can be provided without a significant mass penalty by utilizing part of the MHD disk generator exit flow. A portion of the mass flow would be bled off prior to entering the main effluent control subsystem and ejected through smaller position control nozzles.

TABLE 3-9. NDR/MHD DISK POWER SYSTEM DYNAMIC ACCELERATIONS DUE TO EFFLUENT THRUST IMBALANCES

LH_2 Tank	=	Full	Half-Full	Empty
Space Platform Mass, kg	=	72,960	70,060	67,270
2% Thrust Imbalance, N	=	224	224	224
Translational Accel,(1) m/s^2	=	3.07×10^{-3}	3.20×10^{-3}	3.33×10^{-3}
Pitch Inertia, $kg\text{-}m^2$	=	5.08×10^{6}	4.96×10^{6}	4.85×10^{6}
Lever Arm, m	=	20.40	20.64	20.89
Pitch Accel., Rad/s^2	=	0.90×10^{-3}	0.93×10^{-3}	0.97×10^{-3}
Roll Inertia, $kg\text{-}m^2$	=	0.386×10^{6}	0.379×10^{6}	0.373×10^{6}
Lever Arm, m	=	1.0	1.0	1.0
Roll Accel., Rad/s^2	=	0.58×10^{-3}	0.59×10^{-3}	0.60×10^{-3}

NOTE (1) 2% Thrust Imbalance Acting on C.G.

4.0 POWER CONDITIONING FOR 100 MW SPACE BASED MHD POWER GENERATING SYSTEM

4.1 Basic Requirements

The disk generator loading scheme provides for three separate dc loads with the following parameters:

Section 1	5 kV, 7 kA
Section 2	5.5 kV, 10 kA
Section 3	2.6 kV, 7 kA

The total power is to be delivered to a load operating at 100 kV dc. Total operating time is 500 s, comprising 20 seven second test firings and one ~ 360 s operational burst.

4.2 Basic Power Conditioning Considerations

The voltage ratio is high for true dc-to-dc converters to be used. Thus, the power conditioning approach must be based on dc-to-ac conversion, transformation of the ac, and re-rectification to dc.

The high-current, low voltage character of the generator sections requires, even with the largest switching devices available, parallel connection of devices or converters in the dc-to-ac stage.

The high voltage character of the load requires series connection of rectifier devices, even with the highest available voltage capability. Since current sharing is a requirement in parallel connected units, and voltage sharing is a requirement in series connected units, it follows that the series connection of transformer secondaries can be used to impose current sharing on their parallel connected primaries. Parallel connection of the primaries, in turn, imposes voltage sharing on the secondaries.

Thus, the basic power conditioning topology should be that shown in Figure 4-1. Dc-to-ac converters (inverters) are parallel connected to the generator sections, but each has its own transformer. The transformer secondary voltages are rectified, and the rectifiers are connected in series to provide the dc output. There is a subtle difference between connecting the rectifiers in series and connecting the transformer secondaries in series. If the transformers are in series, then Kirchoff's laws will compel instantaneous adherence to current and voltage sharing, making it impossible to accommodate switching time differences in devices and small regulatory control differences in inverter behavior. Series connecting the rectifiers allows instantaneous values to differ, but enforces average current and voltage sharing.

4.3 Specific Topologies

The specific topology chosen is established by two major considerations. One is the capability of existing switching devices (and diodes), their voltage blocking ratings, and current carrying/switching rates. The other is the need to supply 25 percent of rated power to the load for a short (two to three second) period at the beginning of each test firing and the operational burst.

The generator design proposes to deliver 25 percent power by loading Section 1, with Sections 2 and 3 short circuited by their inverters. Thus a complete 100 kV rectifier assembly must exist for Section 1, with another for Sections 2 and 3. These two rectifiers must appear in parallel when 100 percent load is supplied. For 25 percent load, only that for Section 1 will operate; that for Sections 2 and 3 will block, while the inverters maintain short circuit conditions at the transformer primary sides.

Thus the basic topology expands to that depicted in Figure 4-2. The number of individual inverters and transformers used is determined by device ratings and the particular inverter topology employed.

Since the inverters are connected, in effect, in series at the transformer secondaries, they must appear there as voltage sources (current sources

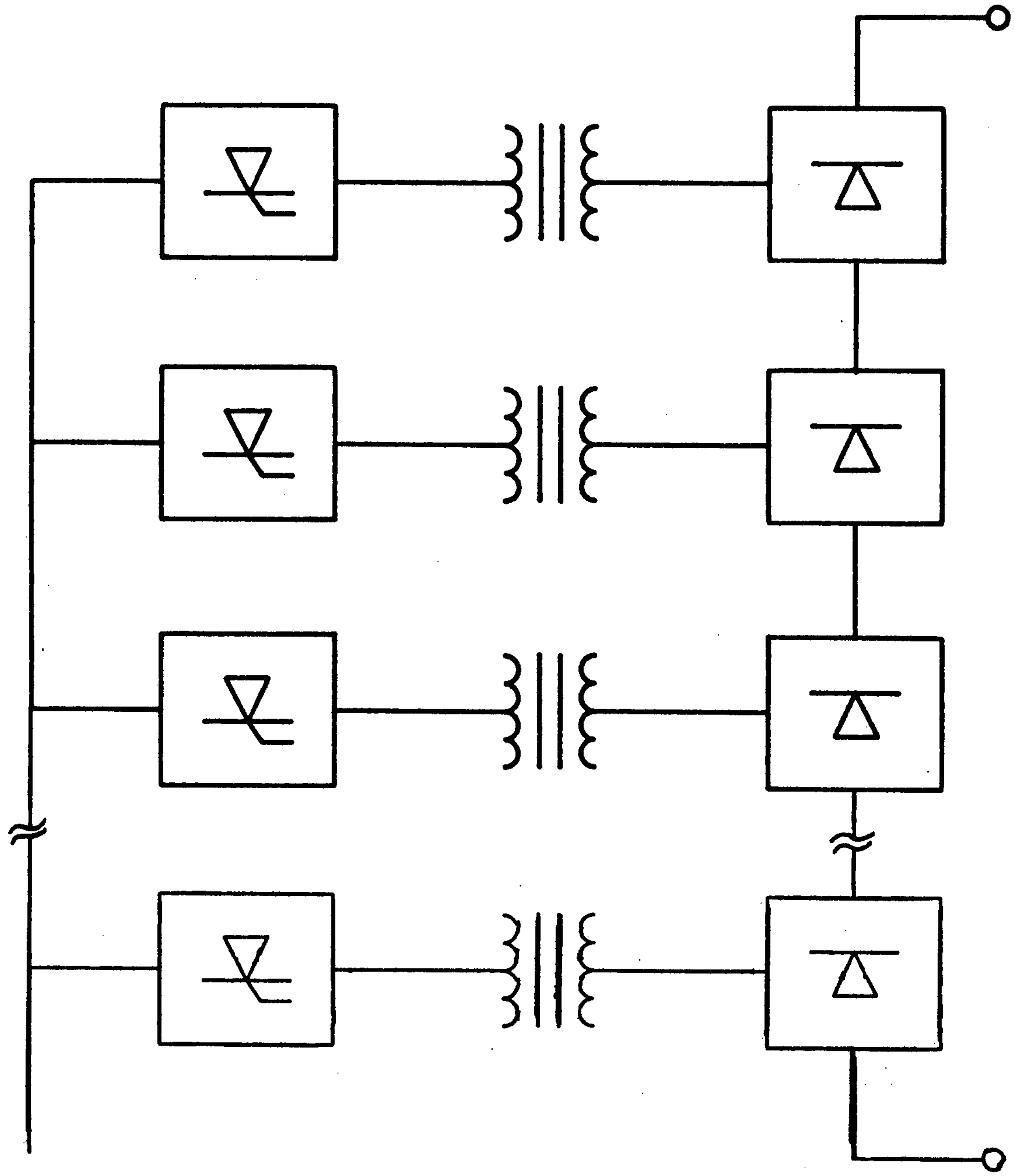


Figure 4-1. Converter Single Line Diagram

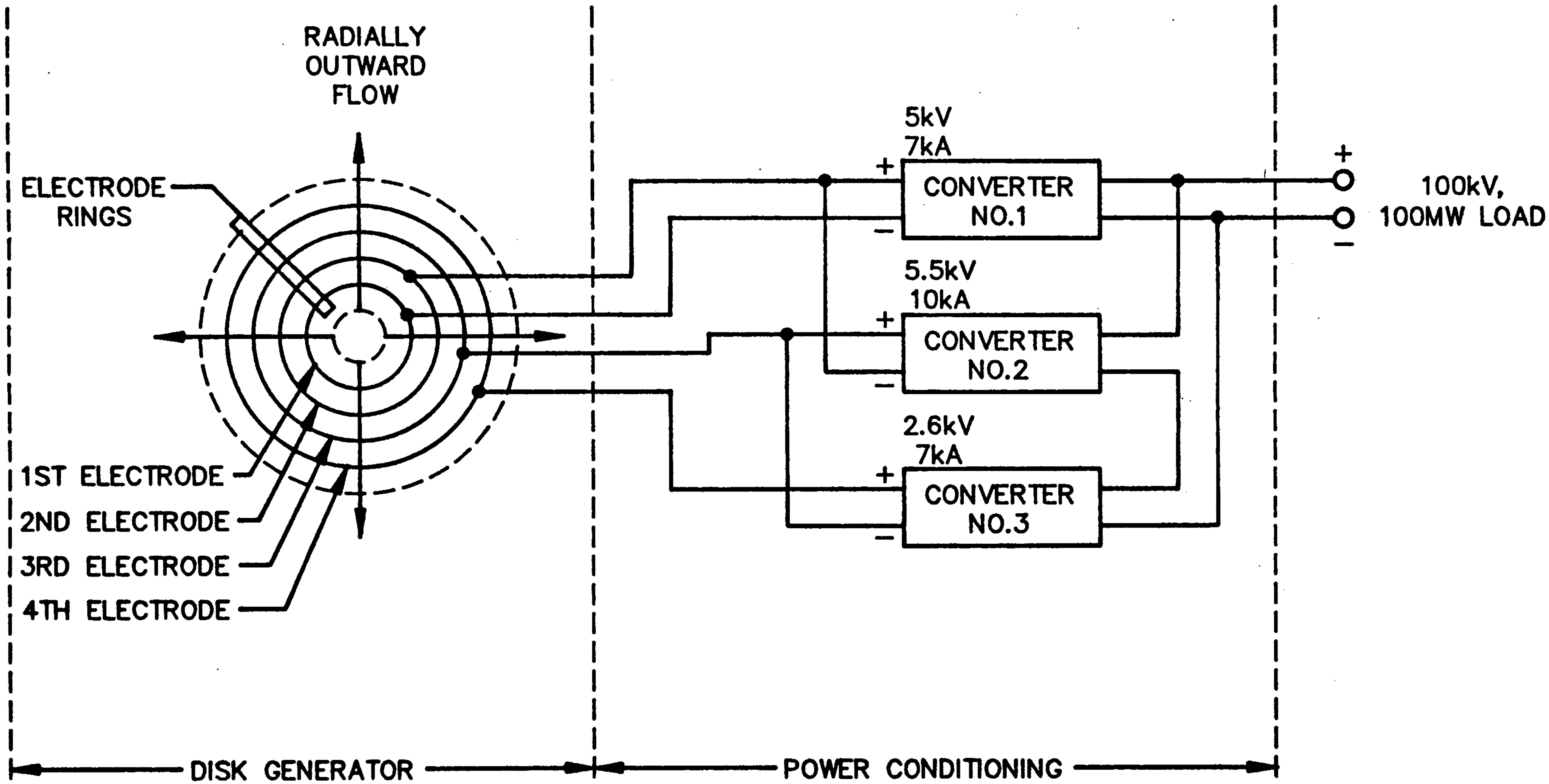


Figure 4-2. Power Conditioning System Configuration

cannot be connected in series). For that to be the case, they must, obviously, appear as voltage sources to the transformer primaries, and therefore must be dc voltage sourced inverters.

The simplest voltage sourced inverter is the self-commutated single-phase bridge topology using field-effect transistors, bipolar transistors, or GTOs as switching devices. Achievable ratings of transistors are so low that the number of devices needed to process 100 MW would be enormous and reliability problems would accrue even for the short operating time required. GTOs are available in high power ratings, currently 4500 V/2500 A (switching) on a 75 mm silicon slice. Even larger GTOs will be available shortly, since 100 mm silicon slices are about to be used for their fabrication. Thus, we have chosen to base the inverter design on a 100 mm, 6 kV/4 kA GTO that should be available in quantity within two years. With appropriate de-rating, the numbers of GTOs needed are as follows:

Section 1:	2 series GTOs; 4 parallel inverters	32 GTOs
Section 2:	2 series GTOs; 6 parallel inverters	48 GTOs
Section 3:	2 series GTOs; 4 parallel inverters	16 GTOs
	Total	96 GTOs

With rectangular waveforms (the simple bridge inverter produces a square wave voltage), three-phase operation affords no advantages as regards input or output filtering. Since the application seeks maximum power transfer per unit mass, three-phase transformers also offer no advantages. Hence the detailed topologies are as shown in Figures 4-3 and 4-4. Figure 4-3 shows a single phase inverter bridge (with two series devices per position) and its transformer and rectifier assembly. For Section 2, the inverters are as shown. For Section 1, the rectifier units expand to 16 devices in series in each leg. For Section 3, the inverter has only one device per leg, and two inverters feed one transformer, with separate primary windings.

Thus, as shown in Figure 4-4, the four inverters for Section 1 feed one side of the output to deliver 25 percent power, with the four rectifier bridges in

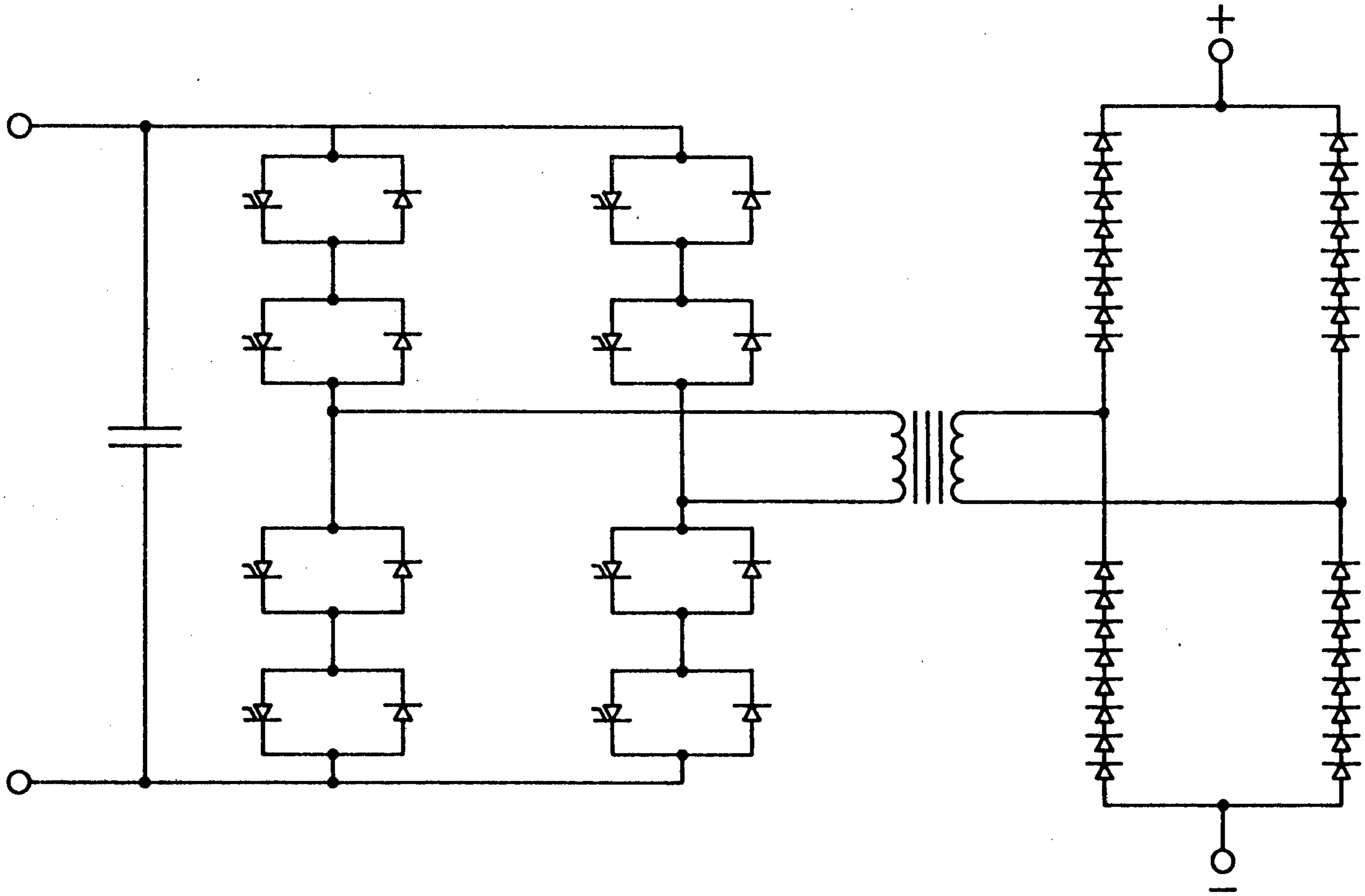


Figure 4-3. Single Phase Inverter Bridge with Transformer, Rectifiers and Input Capacitor (Shown for Section 2 without Snubbers)

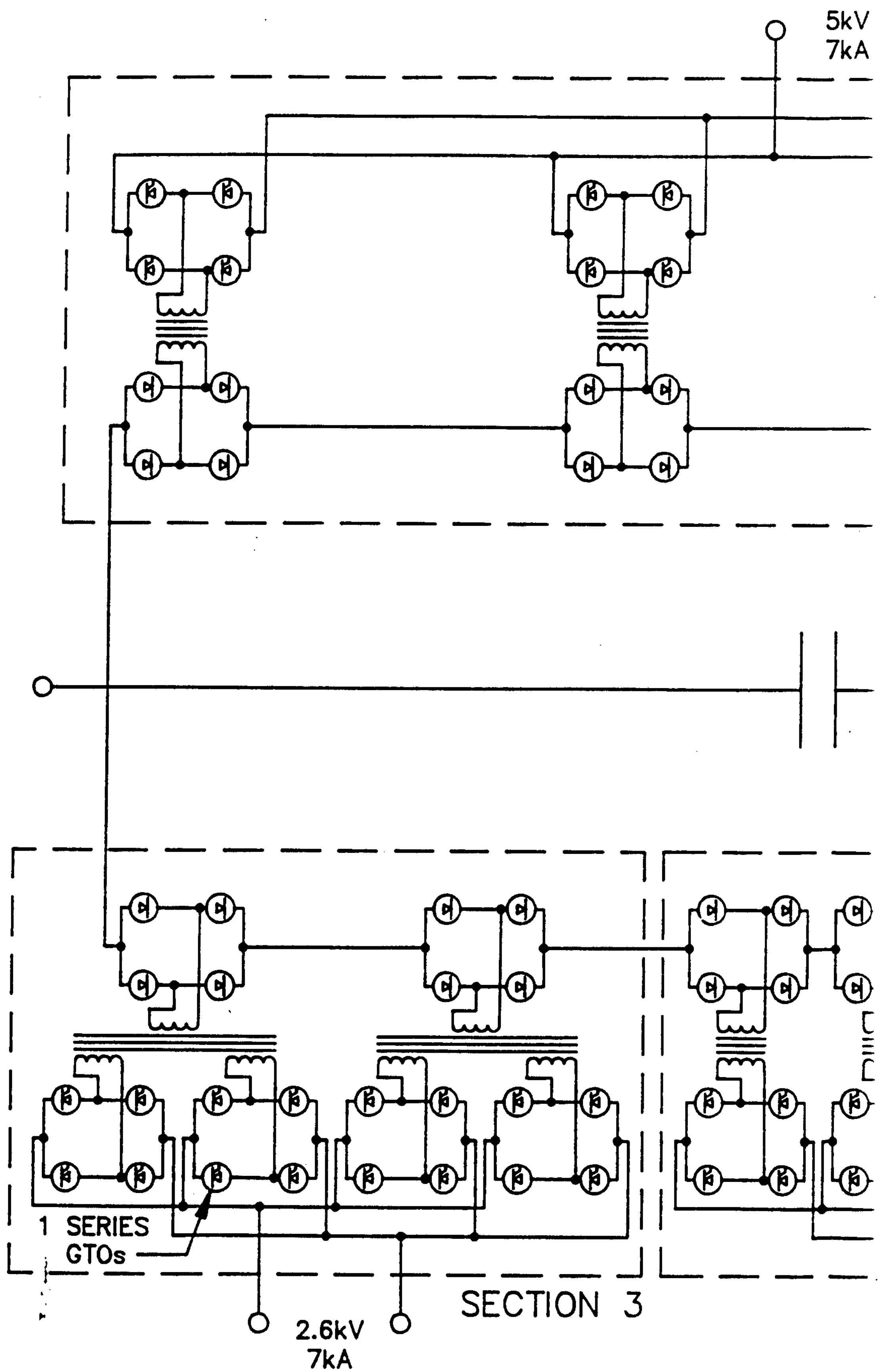


Figure 4-4. Schematic of Overall Power

(1)

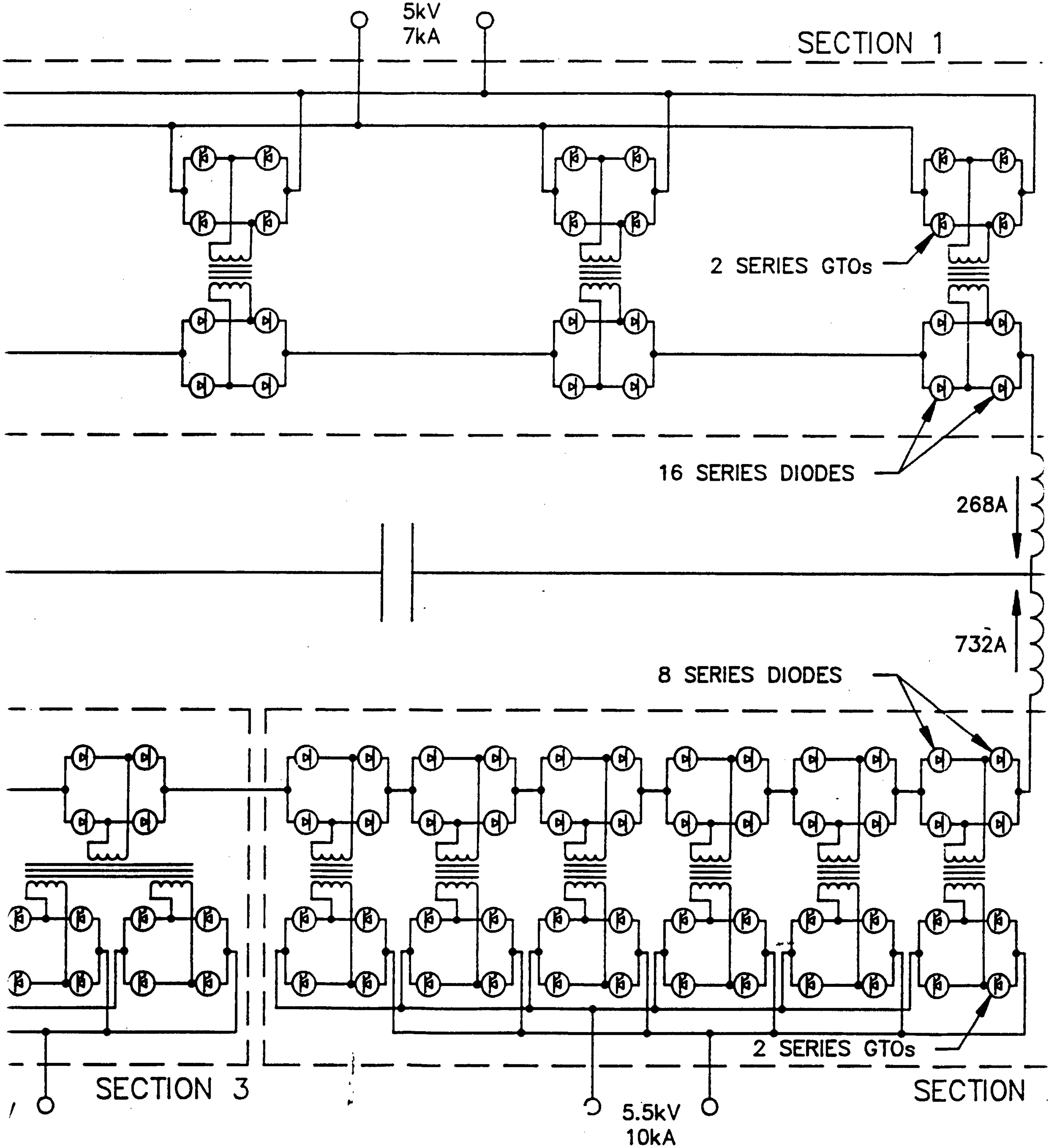
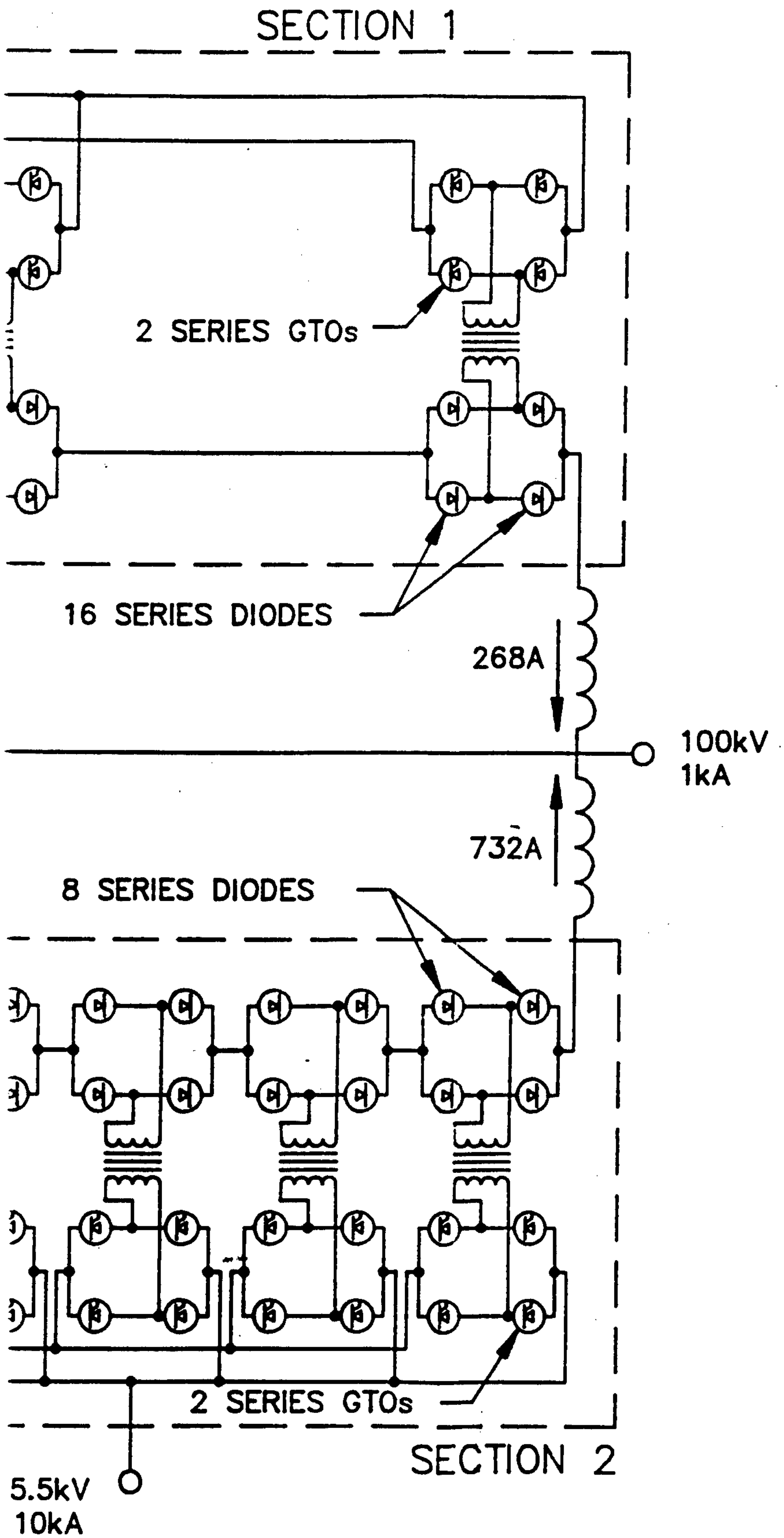


Figure 4-4. Schematic of Overall Power Conditioning System


SECTION 1
2 SERIES GTOs
16 SERIES DIODES
268A
100kV
1kA
732A
8 SERIES DIODES
2 SERIES GTOs
SECTION 2
5.5kV
10kA

;tem

3

series. Sections 2 and 3 feed the other side, to deliver 100 percent power in conjunction with Section 1. The six rectifier bridges of Section 2 are in series with the two composite rectifier bridges of Section 3. L-C filtering is provided to limit output voltage ripple, and to restrict output current ripple.

The input capacitors, appearing at the terminals of each inverter but connected directly in parallel by the dc bus connections, serve to limit ripple voltage applied to the MHD channel by bypassing the ripple currents produced by the inverters.

4.4 Operating Considerations and Mass Calculation

The principal operating variable influencing mass for the power conditioning system is operating frequency. Frequency influences transformer mass, input and output filter masses, and the coolant mass needed for the active devices and their snubber networks. Transformer and filter masses decrease with increasing frequency while the required coolant mass increases.

An upper frequency boundary may be created by the active devices, since they exhibit a heat transfer rate limitation resulting from their packaging and limited operating temperature range. For the system described here, this proved to be the case; a maximum allowable dissipation of 6.2 kW/device limited the operating frequency to 400 Hz.

At this frequency, common transformer steels have no problem absorbing their own losses at full flux capability for 360 s (the longest continuous operating period). Since, other things being equal, transformer mass is inversely proportional to the square of the operating flux density ($m \propto 1/\beta^2$), it was decided to use Supermendur material at 2 T in the transformers. Conductors are limited in current density by their heat absorption capabilities, so unless cooling is provided for the transformer (which increases mass), this becomes a design parameter. A temperature swing of -40°C to 300°C was allowed (the core swing would be much less, to about 80°C). The starting temperature is the lowest at which semiconductor devices will function properly. The final temperature is an arbitrary selection.

With these limits, copper allows 7650 A/in^2 and aluminum allows 5480 A/in^2. Optimum geometry transformer designs, at 400 Hz, showed that the required leakage inductance could be achieved (for maximum power transfer, this is the critical parameter), and that aluminum conductor produced the lightest transformer mass of 700 kg. Note that all the transformers have essentially identical ratings, and hence sizes, with the topology selected. This mass includes the transformer core yokes and mounting brackets/flanges. Thus the transformer mass contribution is 0.084 kg/kW for the whole system.

A GTO of the size required weighs, alone, 1.5 kg. The same diodes are used for the output rectifiers and in the inverters as inverse diodes. Their mass, alone, is 0.8 kg each. Thus the total inverter device mass is 0.0022 kg/kW; rectifier device mass is 0.0041 kg/kW. However, the actual inverter and rectifier units are assemblies with heat sinks, snubbers, and, for the inverters, gate drives. Moreover, they have clamping assemblies to provide the required mounting force for the devices (~ 20 kg for the GTOs, about 10 kg for the diodes), and mounting brackets. Assembled mass for the inverters becomes 0.011 kg/kW; the rectifiers, coincidentally, have exactly the same mass, 0.011 kg/kW.

The output filter mass is calculated to be 0.006 kg/kW, and the mass attributable to controls is 0.002 kg/kW. Input filter capacitors account for another .018 kg/kW, yielding the following tabulation:

Transformers	0.084 kg/kW
Inverters	0.011 kg/kW
Rectifiers	0.011 kg/kW
Output filters	0.006 kg/kW
Control	0.002 kg/kW
Input Capacitors	0.018 kg/kW
Total	0.132 kg/kW

All the major subsystems in the tabulation are complete, self-supporting assemblies with mounting brackets or flanges for attachment to a package frame. The 12 frames involved would then be fitted into the overall, launchable package enclosing the complete system. A fair allowance for the total package mass is 15 percent of the equipment mass, or 0.02 kg/kW (2000 kg, 500 kg for the 12 frames and 1500 kg for the overall package). Thus, the total packaged mass is 0.152 kg/kW (excluding coolant).

In the designs executed, the cooling water required for the active devices and their snubbers was assumed to be available on the spacecraft. If the water cooling system is to be assigned exclusively to the power conditioning, then it adds an additional 0.017 kg/kW to the mass, for a total of 0.169 kg/kW for a completely self-contained power conditioning system.

4.5 Efficiency

The major loss elements in the system are the GTOs (conduction and switching losses), inverter diodes, GTO snubbers, rectifier diodes, rectifier snubbers, and the transformers. Losses calculated for these elements at 100 percent load are tabulated below:

Section 1 GTO conductor losses	118.40 kW	
Section 1 GTO switching losses	70.21 kW	
Section 2 GTO conductor losses	156.96 kW	
Section 2 GTO switching losses	110.35 kW	
Section 3 GTO conductor losses	59.20 kW	
Section 3 GTO switching losses	36.51 kW	
Total GTO losses	551.6 kW	0.552%
Section 1 inverter diode losses	15.47 kW	
Section 2 inverter diode losses	21.71 kW	
Section 3 inverter diode losses	7.74 kW	
Total inverter diode losses	44.92 kW	0.045%

Section 1 snubber losses	371.16 kW	
Section 2 snubber losses	627.82 kW	
Section 3 snubber losses	196.42 kW	
Total snubber losses	1195.4 kW	1.195%
Total inverter losses	1791.9 kW	1.792%
Section 1 rectifier losses	55.91 kW	
Sections 2 & 3 rectifier losses	162.75 kW	
Total rectifier losses	218.66 kW	0.022%
Section 1 rectifier snubber losses	68.27 kW	
Sections 2 & 3 rectifier snubber losses	68.27 kW	
Total rectifier snubber losses	136.54 kW	0.014%
Total Rectifier assembly loss	355.2 kW	0.036%
Total active equipment loss	2147.1 kW	2.147%
Transformer core losses	326.57 kW	0.327%
Transformer conductor losses	1314.14 kW	1.314%
Total transformer losses	1640.7 kW	1.641%
Total system loss	3787.8 kW	
System efficiency at 100 MW output	96.35%	

This seems to be eminently acceptable performance.

4.6 Layout and Packaging

The rationale for "doubling up" the converters for Section 3 was to create a set of modules of identical size, although with differing electrical input and output parameters. Thus the layout and packaging concept is based on 12 physically identical modules.

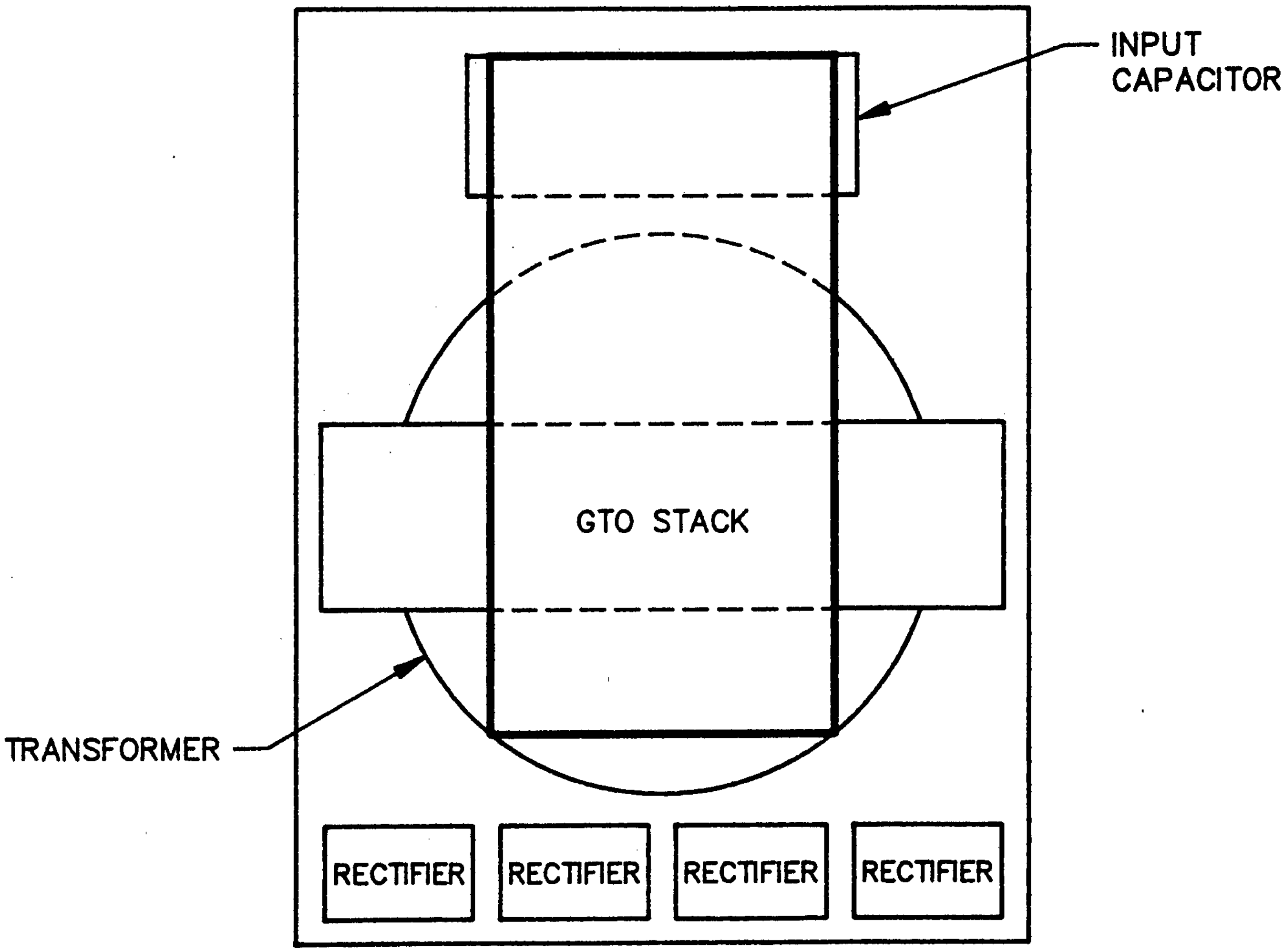
The major component dimensions are tabulated below:

	Width	Height	Depth
Transformer	76.5 cm	61.3 cm	60.6 cm
GTO stack (8 devices)	36 cm	15 cm	72 cm
Rectifier stack (8 devices)	16 cm	72 cm	10 cm
Input capacitors	29 cm	40 cm	16 cm

The module frame is then 100 cm x 80 cm x 90 cm. The layout is straightforward and logical based on an end-to-end power flow, with minimal lengths for interconnections.

As shown in plan view (Figure 4-5), the transformer is the central piece of the assembly. The input capacitors are mounted in front of it with the GTO stack above both the transformer and input capacitors. The rectifier stacks are mounted behind the transformer, which is at the center of the assembly, with the output filter distributed among the 12 units. The total mass of a module is 1267 kg, or just over 1.25 metric tons. The power density in each module is 11.6 W/cm^3.

The overall package is constructed cylindrically for convenient mating with the spacecraft. There is, in fact, a number of options for this package as follows:



(SHOWN FOR SECTION 1, WITH 4 RECTIFIER STACKS. MODULES FOR SECTIONS 2 & 3 HAVE ONLY 2 RECTIFIER STACKS.)

Figure 4-5. Plan View of Module Layout

Module Configuration	Cylinder Diameter	Cylinder Length
1 x 12	1.3 m	10.8 m
2 x 6	1.9 m	5.4 m
4 x 3	2.6 m	2.7 m
6 x 2	3.2 m	1.8 m
12 x 1	4.15 m	0.9 m

These package dimensions do not allow for the water cooling system, i.e. the implicit assumption is made that the cooling is part of a larger system on board the spacecraft.

Cylindrical packaging of rectangular modules obviously involves some volumetric inefficiency; the power densities for the various arrangements are:

Configuration	Power Density
1 x 12	6.98 W/cm^3
2 x 6	6.53 W/cm^3
4 x 3	6.98 W/cm^3
6 x 2	6.91 W/cm^3
12 x 1	8.21 W/cm^3

Despite the volumetric superiority of the 12 x 1 arrangement, the 6 x 2 arrangement (3.2 m dia. x 1.8 m long) is preferred from an electrical viewpoint. The modules can be arranged so that the dc inputs can easily access all modules at their "front edges", while the high voltage outputs can be collected along the center "spine", thus running in an internal sector completely isolated from the inputs. This simplicity, also available in the 4 x 3, 2 x 6, and 1 x 12 arrangement, is lost in the 12 x 1 arrangement.

Apart from the rapid increase in cylinder length, the 4 x 3, 2 x 6, and 1 x 12 arrangements suffer in comparison to the 6 x 2 layout because the high current input buses have to run for greater distances. This is not a trivial consideration, since conductor mass would increase as a result.

4.7 Conclusions

The power conditioning system described is simple, efficient and low mass. Nevertheless, out of this single point exercise, without optimization, several concerns arise for future design work.

Transformer mass clearly dominates, being approximately one-half of the total mass. Further work should concentrate on reducing transformer mass by increasing operating frequency, or possibly by eliminating the transformer altogether through the use of dc-to-dc conversion technology with a higher voltage source. In addition to the significant reduction in mass, the transformer losses would also be eliminated, although active device losses would increase.

Device snubber losses are also a point of major concern, since they account for 62 percent of the active equipment loss, and further increases in operating frequency will increase both their absolute values and relative importance. Their mass impact is felt mainly in the water cooling system. Means to reduce snubber losses, other than simply improved switching devices, may be available through snubber energy recovery techniques.

Resonant converter techniques are probably not appropriate, since changing the simple converter used in the exercise to a resonant converter requires a threefold increase in operating frequency just to achieve the same mass, other things being equal. However, such an increase will probably bring the counter effects of ac-to-dc resistance ratio (skin, proximity and eddy current effects) into play in the transformer conductors, negating, at least in part, mass reductions.

5.0 RESEARCH AND DEVELOPMENT PLAN FOR TASK 2

The scope of this project (Phase 1) is to define MMW space-based MHD systems as power sources for SDIO mission applications, and to identify and resolve specific technical uncertainties associated with these systems.

Phase 1 is being performed in two tasks (Figure 5-1). With Task 1 (completed January 1988), a specific space-based MHD power system and its component elements have been identified and described; a conceptual design has been prepared; technical uncertainties associated with these systems have been specified; and plans (including tasks, schedules and costs) to resolve these uncertainties have been developed.

Task 2 of the Phase 1 effort will involve implementation of the plans developed in the first task, subject to approval by DOE/PETC to proceed. This section of this supplemental report reviews these plans to resolve the issues identified.

The general approach that was used in Task 1 is shown in Figure 5-2 to indicate the sequence of activities that occurred. Task 1 was initiated with the definition of power system requirements and design guidelines. This effort represents a refinement of the requirements discussed in our proposal. When the requirements were sufficiently refined and agreed upon, system parametric studies were initiated. In parallel, efforts on defining and refining the key technical issues were begun. All of these activities were required before the preparation of the power system conceptual design could be started. When that design was completed, it comprised the basis, along with the key issues, for the preparation of the R&D Plan for Task 2. As shown in Figure 5-2, the power system conceptual design and the Task 2 R&D Plan are major end products of Task 1.

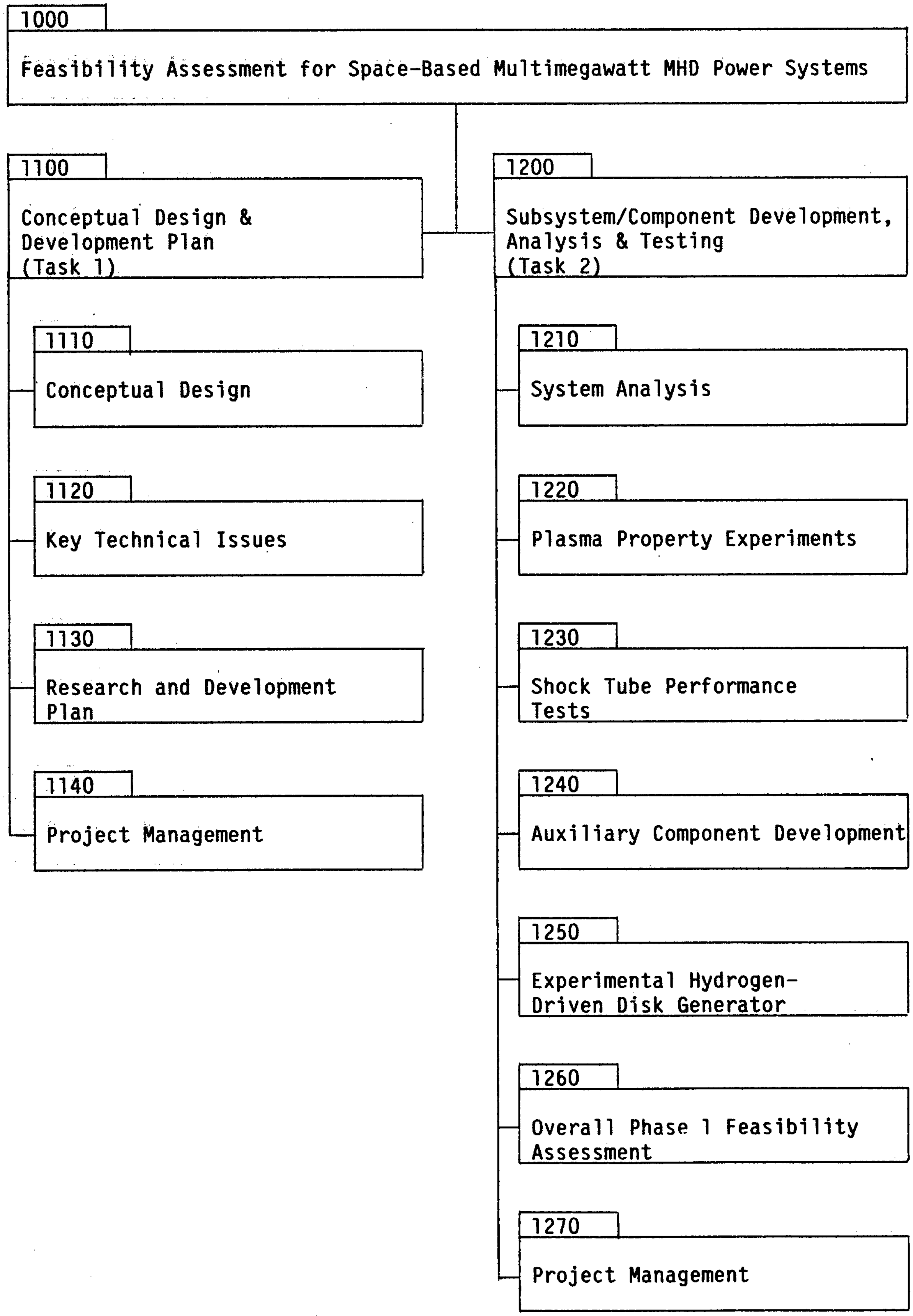


Figure 5-1. Phase 1 Work Breakdown Structure

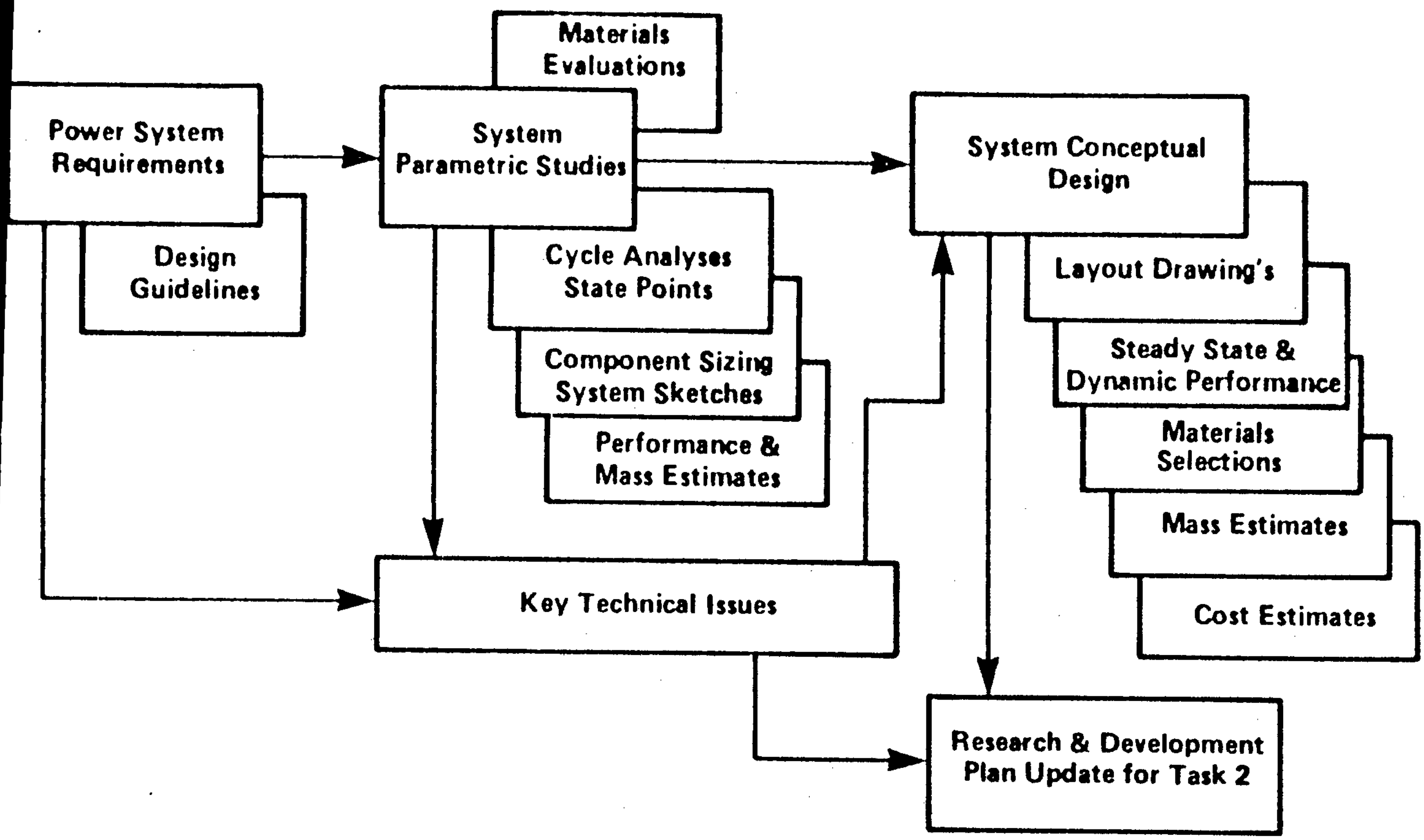


Figure 5-2. Task 1 General Approach

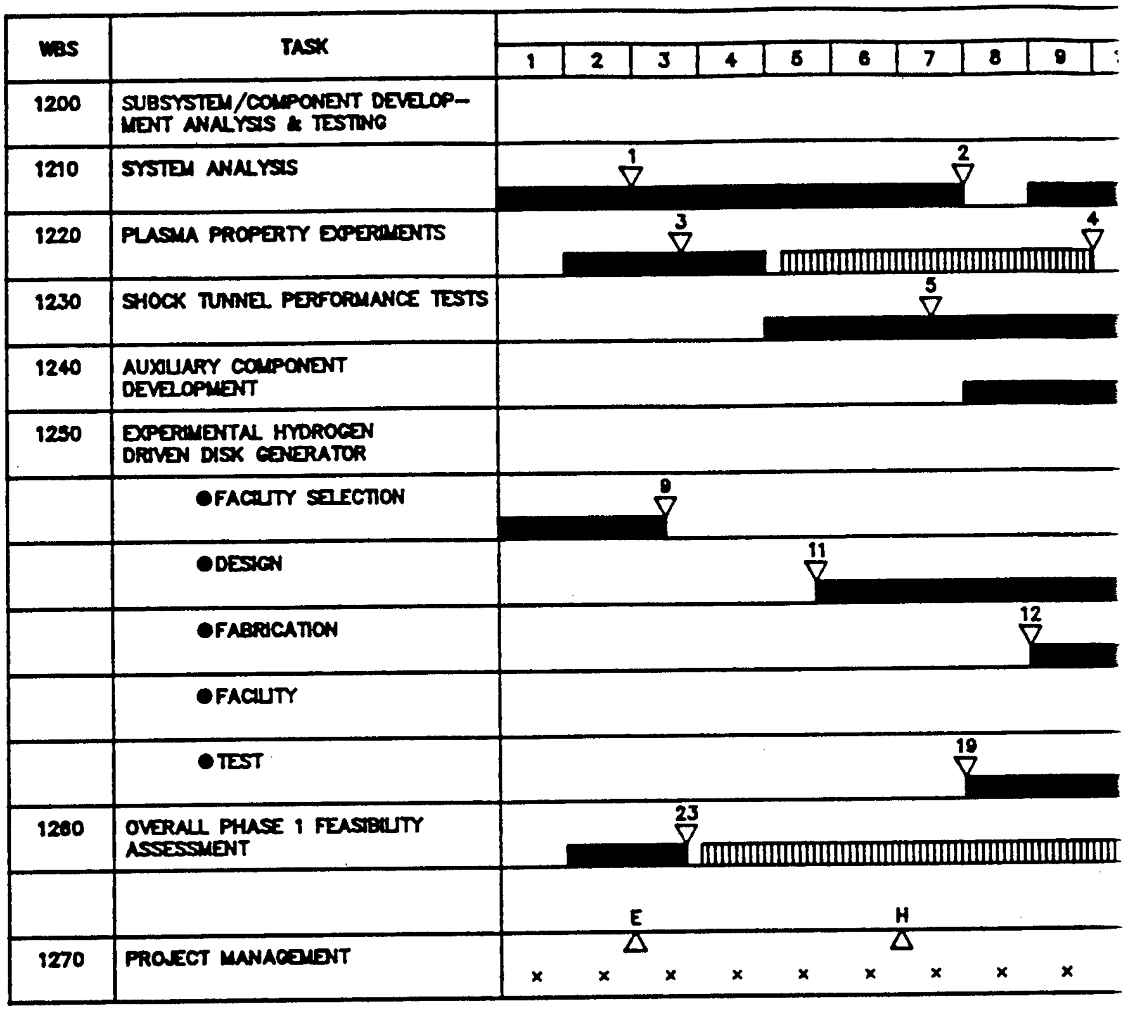
5.1 Task 2 - Subsystem/Component Development, Analysis and Testing

Task 2 is a 24 month program intended to fully assess the technical feasibility of a hydrogen driven disk MHD generator. The Task 2 Work Breakdown Structure is devised so that an on-going analysis task mutually complements a series of disk generator-related experiments and tests. These experiments culminate with the fabrication, assembly and test of a multimegawatt experimental disk generator. This configuration, to be tested with seeded hydrogen heated to design temperatures by plasma torches, is intended to conclusively demonstrate operational stability and the high enthalpy extraction that is unique to our concept.

The Task 2 WBS and schedule are shown on Figure 5-3. Six major technical subtasks are defined. Four of these subtasks cover engineering development and tests of experimental disk generators and related components. A system analysis subtask (WBS 1210) provides a concurrent analytical effort that resolves specific technical issues and interacts with all of the development/test efforts. The Phase I feasibility assessment will be completed and documented under WBS 1260. This subtask will provide the synthesis of all of the other efforts from Tasks 1 and 2 and will include the preparation of an updated MMW/MHD power system conceptual design.

As can be seen from the schedule of Figure 5-3, Task 2 is devised so that the experimental effort culminates in a test program with a nominally 5 to 10 MW (thermal) input, hydrogen driven disk generator. This device, which will be designed, built and tested under WBS 1250, is intended to verify the predicted performance stability and operating efficiency of the concept. Tests with this experimental generator will verify the analytical and plasma experiments and confirm the Phase I level feasibility assessment.

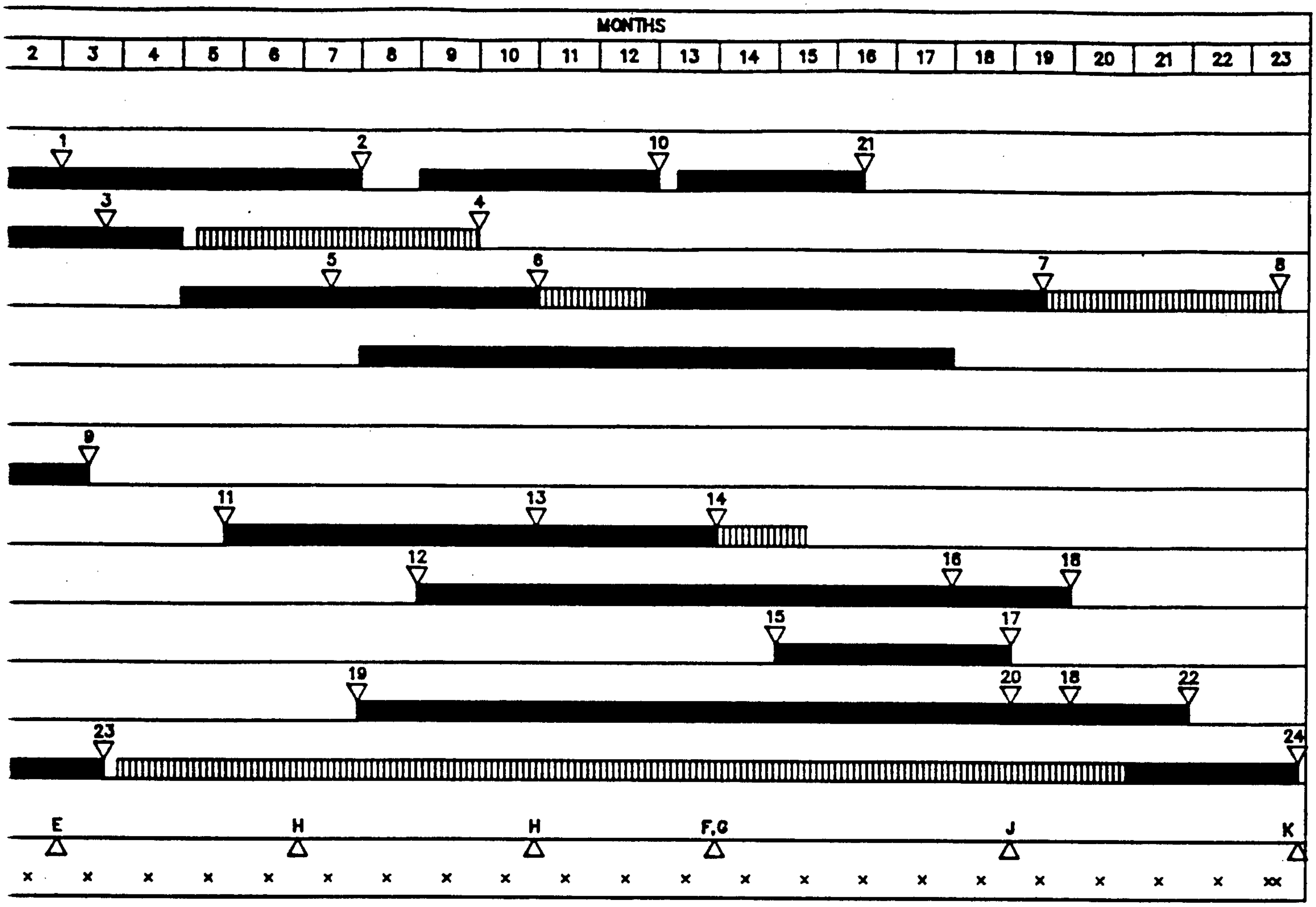
Before the experimental hydrogen disk generator is designed and built, a set of disk generator experiments is to be performed at MIT using the existing shock tube disk generator test facilities. The first set of these experiments, under WBS 1220, is designed so as to determine plasma



MILESTONE SCHEDULE & STATUS REPORT

TASK 2 KEY EVENT

1. Analysis plan issued
2. Issue guidance to shock tunnel performance tests
3. Plasma conductivity demonstrated and other plasma measurements initiated
4. Topical report draft on plasma properties
5. Nonequilibrium performance demonstrated
6. Generator low B field performance measurements completed
7. Generator high B field performance measurements completed (with reversed field)
8. Generator performance data report
9. Facility review and recommendation completed
10. Model update incorporating shock tunnel test results
11. Initiate endurance experimental disk generator design
12. Order long lead materials
13. Preliminary design review
14. Endurance generator design co
15. Plasma torch procurement co
16. Endurance generator fab/asse
17. Test facility modifications com
18. Test article installed and chec
19. Preliminary test plan issued
20. Final test plan
21. Analysis guidance to test plan
22. Endurance disk generator test
23. Preliminary 100 MWe space sy
24. o Updated 100 MWe concept
    o Final Phase 1 system spe
    o Phase 2 draft program pl



E & STATUS REPORT

EY EVENT

measurements

pleted

npleted (with

14. Endurance generator design complete
15. Plasma torch procurement complete
16. Endurance generator fab/assembly complete
17. Test facility modifications complete
18. Test article installed and checked out
19. Preliminary test plan issued
20. Final test plan
21. Analysis guidance to test plan submitted
22. Endurance disk generator tests complete
23. Preliminary 100 MWe space system specification
24. o Updated 100 MWe conceptual design
    o Final Phase 1 system specification
    o Phase 2 draft program plan issued

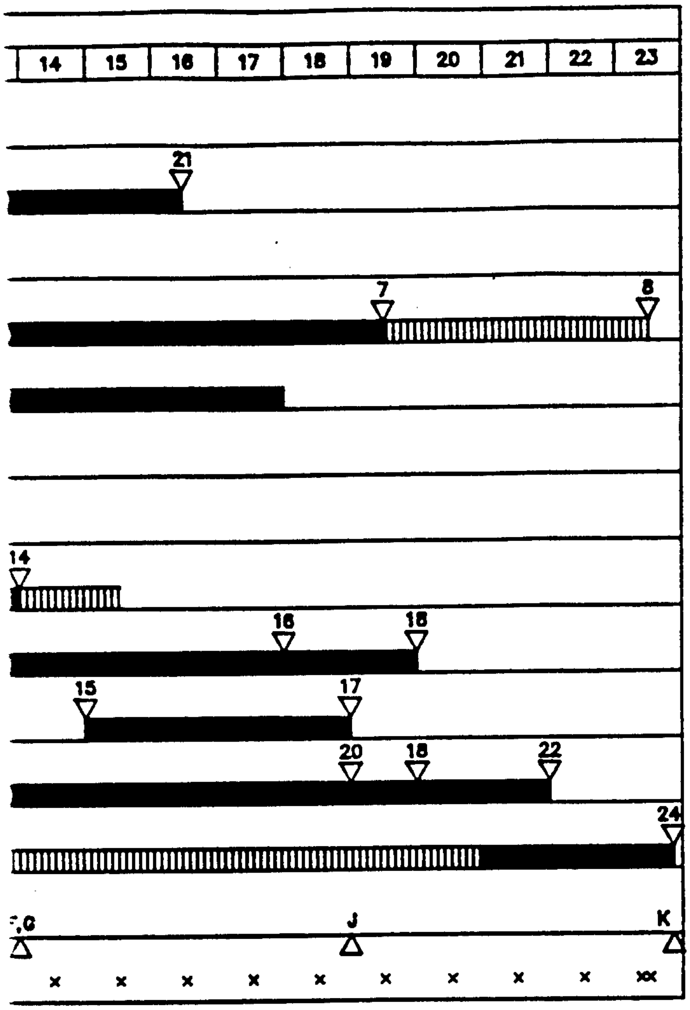
DELIVERABLE DOCUMENTATION

Deliverable Item	Description	Applicable WBS
TASK 2		
E	Detailed Test Plan (for each test or test series)	1270
F	Test Component/Subsystem Design Report	1270
G	Test Component/Subsystem Assembly and Installation Drawings	1270
H	Preliminary Test Reports	1270
J	Topical Reports of Analytical Studies	1270
K	Draft Final Technical Report	1270
X	As Specified by URSC*	

*Uniform Reporting System for Contractors

MHD880106-12C

Figure 5-3.



DELIVERABLE DOCUMENTATION

Deliverable Item	Description	Applicable WBS
TASK 2		
E	Detailed Test Plan (for each test or test series)	1270
F	Test Component/Subsystem Design Report	1270
G	Test Component/Subsystem Assembly and Installation Drawings	1270
H	Preliminary Test Reports	1270
J	Topical Reports of Analytical Studies	1270
K	Draft Final Technical Report	1270
X	As Specified by URSC*	

*Uniform Reporting System for Contractors

MHD880106-12C

Figure 5-3. WBS and Schedule for Task 2

3

properties with hydrogen (impact is determinable with hydrogen in argon levels over 5 percent) in the range of pressures, temperatures and Hall coefficients of interest. The second set of experiments, which are under WBS 1230, also use the MIT shock tube facility. These experiments, however, are aimed at determination of disk generator performance using a mixture of argon and hydrogen. Three physical regions of the generator are to be examined: the conventional section located in the inner base of the magnet, a section located between the coils, and a section located just downstream of the outer diameters of the coils.

After determination of plasma properties and analytical model verification with these experiments are successfully completed, the design and fabrication of the multimegawatt experimental disk generator can proceed with confidence. These efforts, with related facility modifications, assembly, checkout and testing, are under WBS 1250.

DETAILED WORK STATEMENTS

A set of detailed Work Statements for Task 2 follows consistent with the WBS and schedule shown in Figure 5-3 and written to the third level (subtask) WBS.

WBS 1210 - SYSTEM ANALYSIS

<u>Objective</u>: To perform well defined system analyses of both steady state and dynamic performance aspects of the nuclear driven disk MHD generator system and to provide analytic and design guidance for definition of experiments planned under other subtasks.

<u>Approach</u>: Evaluate existing analytical models of disk generator and NERVA reactor performance, and determine where gaps occur in assembly of an analytical system consisting of the reactor, disk MHD generator and other subsystems. Modify and refine the existing models and create new models, such as a constant electron temperature model and a fixed geometry model,

for the SPA code. Develope dynamic models to synthesize the overall power system. Mechanize this model on appropriate digital (e.g., CRAY) or hybrid computers, checkout the codes and initiate design related studies. Analyze the results from these early studies, incorporate experimentally-based plasma properties, and provide guidance to the shock tube experiments scheduled at MIT. Obtain feedback from these experiments and modify/refine the models as needed.

Perform additional studies that simulate the planned test configuration for the multimegawatt hydrogen driven disk generator. From these studies, provide design and test guidance to WBS 1250. Obtain feedback from the test results and further refine the model parameters as appropriate.

Use the refined model following the experimental hydrogen driven disk generator test results to perform additional analyses that guide the preparation of the updated conceptual design of the 100 MW_e space-based power system.

WBS 1220 - PLASMA PROPERTY EXPERIMENTS

Objectives: To gain a good, experimentally based understanding of the properties of the type of plasma expected for the nuclear driven MMW/MHD disk generator.

Approach: Use the existing shock tube disk MHD generator facility at MIT for these experiments. Determine required experimental measurements for plasma properties and determine additional instrumentation if required. Submit experimental plan for DOE approval and prepare an experimental procedures document. Modify the facility as needed and as indicated by an overall test plan for this subtask. Perform the experiments with seeded inert gas (argon) with sufficient hydrogen added to dominate the plasma behavior. Analyze the data from the experiments and determine the appropriate plasma properties in the range of pressures, temperatures and Hall coefficients of interest. Input this data into WBS 1210 for incorporation of plasma property data into analysis programs.

WBS 1230 - HYDROGEN/INERT GAS SHOCK TUBE PERFORMANCE TEST

Objective: To obtain experimental verification of the predicted performance of the disk generator for three distinct regions of the generator.

Approach: Use the MIT shock tube facility to conduct a set of short duration experiments that provide measurements of MHD performance in three sections of the disk generator. First, evaluate the performance in the conventional section of the generator located in the inner base of the magnet. Next, evaluate the performance in a section located between the coils, and third, evaluate a section located just downstream of the outer diameter of the coils. For these experiments, place special purpose electrodes in the appropriate locations for each of these sections of the shock tube and use the voltage and current measurements obtained from these electrodes as the primary performance indicator. Also, determine other key experimental measurements needed from these tests and instrument the shock tube facility accordingly. Analyze the data from these experiments and use the results in conjunction with the shock wave calculated power input to the generator to assess the relative enthalpy extraction from each section.

WBS 1240 - AUXILIARY COMPONENT DEVELOPMENT

Objectives: Pursue design and engineering development activities on several key components in the system where significant uncertainties have been identified. Electrode design configuration and materials selection, seed mixing in the hydrogen stream, and power conditioning interface definitions between the MHD generator/weapons system represent areas of concern.

Approach:

Seed Mixing: Evaluate the characteristics of seed feed variations and control requirements utilizing computer models and compare to capability of seed feed and mixing system concepts. Identify suitability of electric heating of pressurized seed vapor and metering control for feed and mixing of very low molar percent cesium into heated hydrogen at up to 40 atmospheres pressure. Correlate results from MIT shock tube experiments with analytical model and verify that seed feed can meet predicted requirements. Define component test requirements, specify and design tests, and make test predictions for experimental disk tests which will be conducted under WBS 1250.

Insulation and Electrode Development: Evaluate state-of-the-art insulation and electrode technology for disk MHD generators as compared to the particular requirements imposed by this application. Identify suitable materials of construction and fabricate experimental configurations predicated on the Task 1 disk MHD generator conceptual designs. Investigate test requirements and determine whether suitable component testing is required under this subtask. Specify test requirements unique to the components defined for the experimental disk MHD generator under WBS 1250.

Power Conditioning: Use the interface requirements and definition between the burst power system and the SDI weapons platform to specify a set of power conditioning development efforts. From the system analysis subtask (WBS 1210), obtain estimates of the expected waveforms, duty cycle and noise likely to be superimposed on the output of the power conditioning system and the noise present on the output of the disk MHD generator terminals. Determine the impact of these characteristics on power conditioning circuits for the mission systems and magnet power supply.

Perform literature reviews of related programs to evaluate the long term effects of the space environment and power system induced environment (e.g., nuclear radiation and magnetic fields) on power conditioning components and insulating materials. Evaluate specific circuit configurations for magnet power conditioning and determine the feasibility of building a scaled version of this circuit for tests with the experimental disk MHD generator under WBS 1250.

Evaluate the relative merits of coaxial power transmission lines and conventional cable systems by considering mass savings, dual use of hydrogen piping, and combining lines with system structure.

WBS 1250 - EXPERIMENTAL HYDROGEN DRIVEN DISK GENERATOR

Objective: To demonstrate, at the multimegawatt level, the high performance potential of hydrogen driven disk MHD generators. More specifically, to build and test an experimental disk generator for at least 100 s continu- ously, and during these tests to obtain generator power density data that verifies that the 100 MW_e disk would attain enthalpy extractions exceeding 50 percent.

Approach: When Task 2 is initiated, a detailed facility modification/cost review will be completed, and a site recommendation will be presented. Prepare a detailed plan for testing of the MMW experimental disk generator and use the ongoing results from WBS 1210, WBS 1220 and WBS 1230 as guidance in preparing this plan. Prepare the preliminary design of the disk MHD generator and identify overall test facility requirements and needed modifications to the CDIF to accommodate this test.

Prepare a detailed design of the MMW experimental disk generator and initiate procurement of long lead materials. Finalize the design, issue an RFQ for fabrication, and evaluate "Make or Buy" orders for major generator components: magnet, disk, structure, insulated walls, electrodes and electrical interconnecting equipment. Prepare specifications for component acceptance testing and monitor these tests at fabricators' facilities.

Initiate design and procurement activities at CDIF based on the facility requirements document. Include the cryogenic system for the magnet, magnet power supply (if self-excited magnet is not used), power supply and substation alteration for the plasma torch arc heater, provisions for resistive load for MHD generator electrical output, generator test stand, supplies of liquid hydrogen, cesium seed injection system, plasma torch equipment to heat hydrogen, pumping equipment, and equipment for handling/venting of generator plasma exhaust.

Complete the test facility design activities requiring facility modifications, including unique instrumentation and control requirements. Assemble the MMW experimental generator and ship to CDIF for installation. Install the generator onto the test stand and integrate it with the plasma torch. Integrate the test article with structural, electrical and thermal facility interfaces and perform functional checkouts.

Verify facility and test article readiness and conduct ongoing safety reviews and approvals. Prepare final operational and safety documentation and obtain approvals for power testing.

Conduct a series of generator power tests in accordance with the final overall test plan. Evaluate the results, analyze performance and provide feedback to WBS 1210 for reconciliation with generator design performance models.

WBS 1260 - OVERALL PHASE I FEASIBILITY ASSESSMENT

Objective: To perform the Phase I feasibility assessment of the nuclear disk MHD generator concept for space-based applications and recommended scope of Phase II of the program. Phase II will represent the final feasibility assessment.

Approach: Early in Task 2, initiate a power system specification with major input from Boeing for the 100 MW_e space application design concept based on the conceptual design prepared in Task 1. For purposes of this specification, identify, with SDIO concurrence, one or more specific weapon systems as a basis for defining the specific and detailed power system/space platform interfaces in this specification.

Use the 100 MW_e System Specification as a "living document" throughout Task 2. Incorporate evolving requirements that relate to space environment operational modes and mission system demands. Use the pertinent results of other design studies sponsored by SDIO/DOE on MMW gas-cooled (NERVA derivative type) reactors as they pertain to this power system. This particular activity will permit this contract to take advantage of the work on MMW gas-cooled reactors with a modest commitment of funds from this contract. In effect, the bulk of the nuclear reactor-related issues from Task 1 (WBS 1120) will be dealt with effectively and economically during Task 2 as part of this subtask (WBS 1260).

From the system analysis results (WBS 1210), all of the results of the experimental efforts in Task 2 (WBS 1220, 1230, 1240 and 1250), and the 100 MW_e System Specification (WBS 1260), prepare the updated system conceptual design. Use the design concept from Task 1 (WBS 1130) as the basis for this updated design. When the design update is complete, incorporate it into the System Specification.

Use all of the results discussed above to prepare a Phase II recommended program for the design, fabrication and testing of a full 100 MW_e ground prototype system to be driven by a NERVA derivative reactor.

WBS 1270 - PROJECT MANAGEMENT

Objective: To ensure effective management of the project via schedular and cost control, technical direction of Westinghouse and subcontractor activities, timely submittal of deliverable items, and frequent customer communication.

Approach: Use techniques and tools such as Westinghouse Integrated Management and Control System (IMACS), Action Commitment Expediting System (ACES), Work Authorization and Subcontractor Management system tailored to the needs of this program. Prepare reports and submit to DOE in accordance with the Reporting Requirements Checklist.

6.0 COMPARISON OF DISK MHD GENERATOR WITH BRAYTON TURBO-GENERATOR POWER SYSTEMS

Open cycle multimegawatt (MMW) space nuclear power systems are attractive candidates to satisfy the burst power needs of SDI systems. The basic concepts are open cycle power conversion systems powered by hydrogen heated in a NERVA Derivative Reactor (NDR). A comparison between Brayton turbo-generators and MHD power conversion/power conditioning system is made at a net dc output power of 100 MW_e. The space-based power systems concepts are considered to power a generic, tube type Neutral Particle Beam (NPB) that requires semi-annual testing. For the MHD system operation, liquid hydrogen enters the system and cools the power conditioning subsystem (Figure 6-1), the reactor support structure, the MHD generator walls, and the reactor outlet nozzle walls. A separate hydrogen circuit is used to cool the magnet. A very low concentration cesium seed (about one third of a percent by weight) is added to the hydrogen before it enters the reactor inlet plenum. The reactor supplies the high temperature, lightly cesium seeded hydrogen to the MHD disk for electric power production in the generator. After power production, the gas leaves the disk generator through two exhaust nozzles which are diametrically opposed to minimize attitude control requirements.

The baseline functional arrangement of the Brayton turbo-generator system is illustrated in Figure 6-2. It shows that liquid hydrogen is stored in a refrigerated storage tank insulated with multilayer insulation. Prior to entering the turbines that drive the hydrogen pumps, the hot hydrogen bled from the reactor exit is cooled by mixing with cold hydrogen bled off the reactor inlet. Power control below the rated level is effected by means of a bleed valve on the inlet to the turbo-pump turbines.

The pressurized liquid hydrogen leaving the turbo-pumps passes through two heat exchangers used to cool the weapon system and the prime power conditioning equipment. Upon exiting the heat exchangers, the hydrogen is at a temperature of ~ 400 K. A significant amount of energy is recoupled

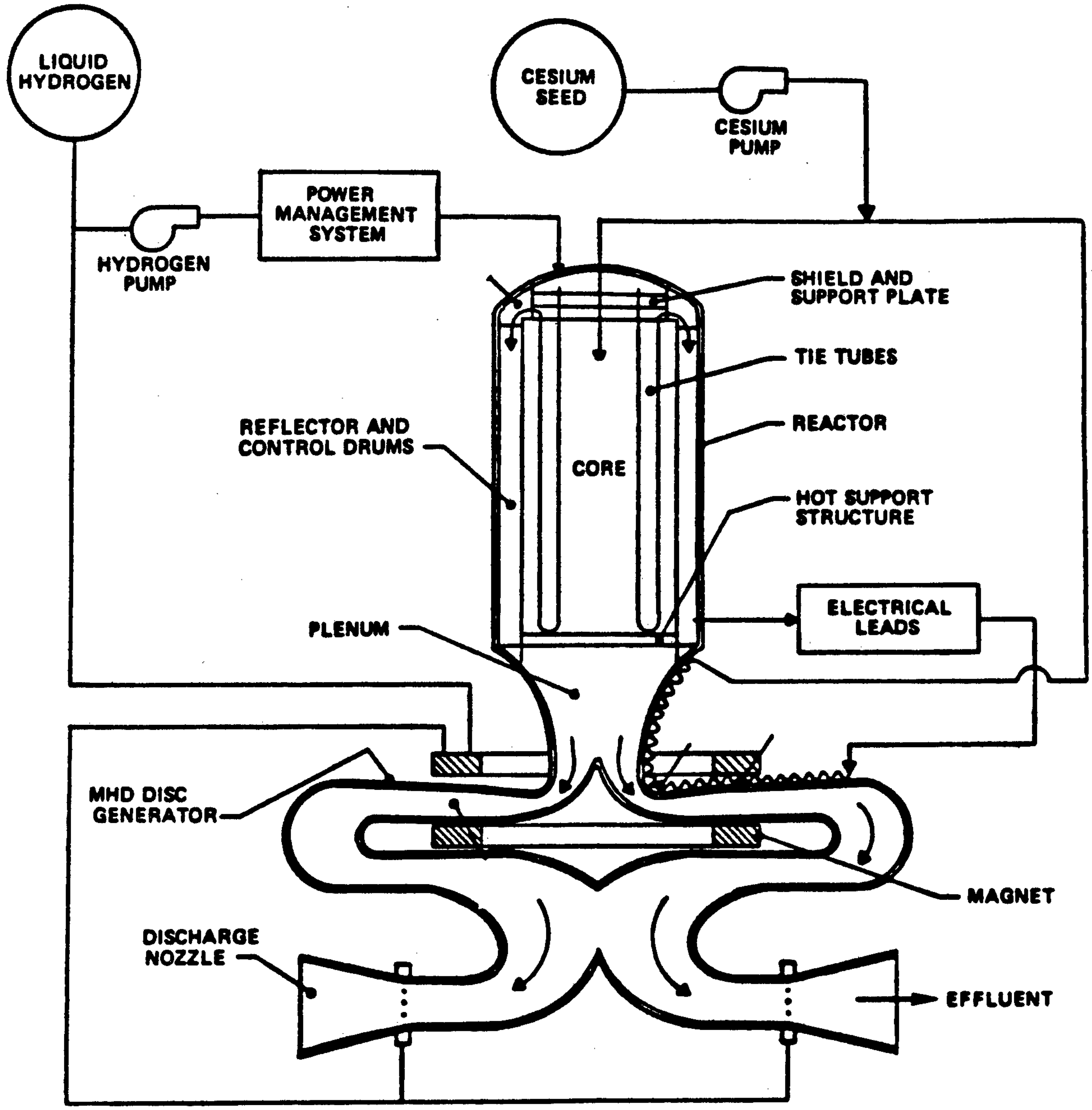


Figure 6-1. Overall MHD Power System Concept

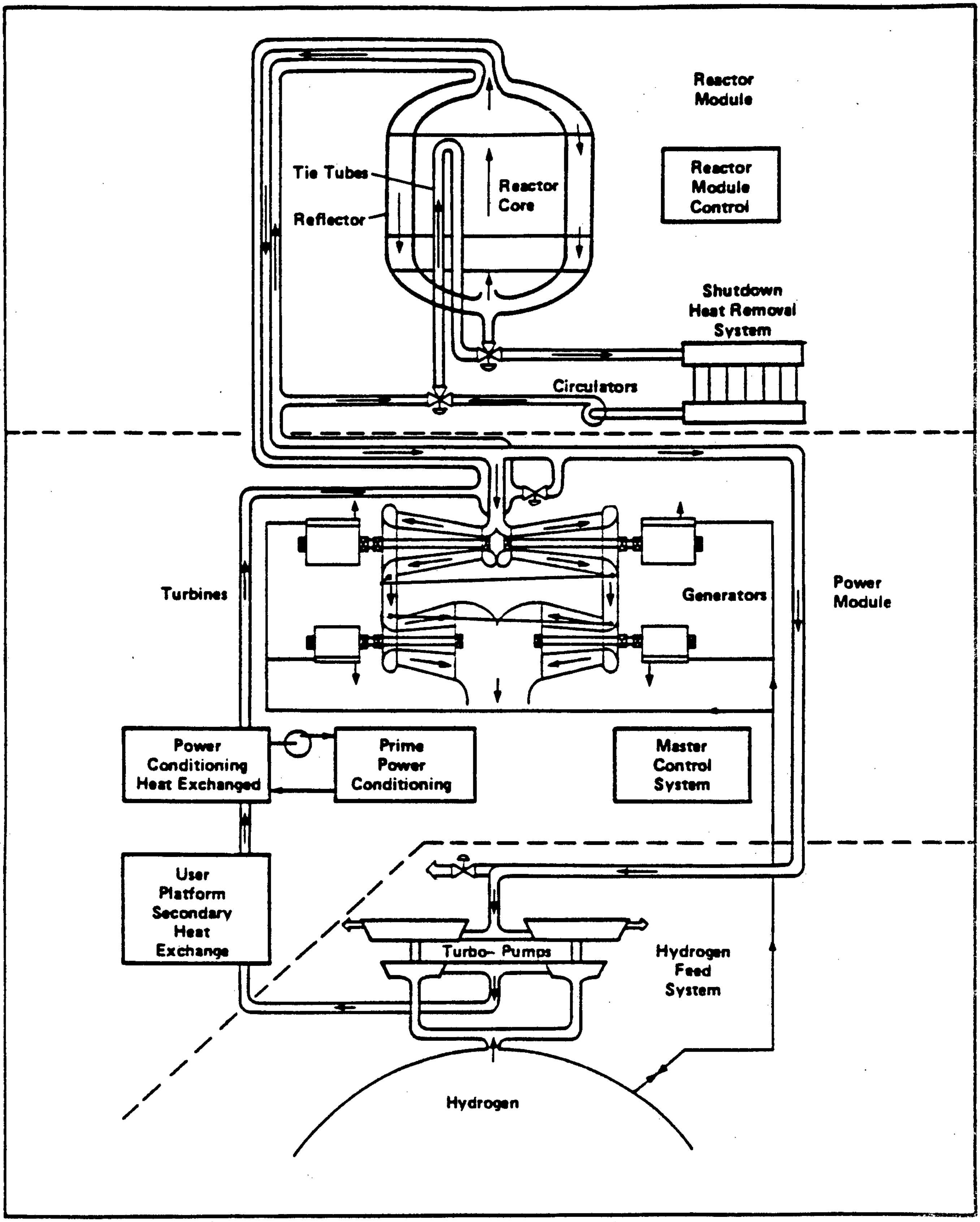


Figure 6-2. NDR/Brayton Turbo-Generator Space Power System

because of the inefficiencies in the weapon and the power conditioning systems.

Upon reaching the reactor, the hydrogen flow splits with approximately 90 percent flowing into the base of the reactor and around and through the reflectors. The remaining 10 percent enters the top of the reactor, flowing through the tie tubes and rejoins the bulk of the flow prior to passing through the main coolant channels. The flow exits the reactor at 1700 K. Two three-way valves can isolate the tie tubes from the main flow forming a closed loop shutdown heat removal system. The heat is radiated to space via an array of hardened heat pipe radiators.

The hot high pressure hydrogen exiting the reactor passes sequentially through a pair of counter-rotating high pressure and low pressure axial turbines. Each pair rotates on a common axis. The expanded hydrogen exiting the low pressure turbines is exhausted through counter-venting actively controlled nozzles.

Each of the four turbines drives a hyperconducting generator cooled by liquid hydrogen taken directly from the hydrogen storage tank. Three-phase ac power is rectified and filtered to the specified conditions by the prime power conditioning equipment. This equipment is housed in a pressurized vessel of inert insulating gas (SF_6).

The power conversion energy extraction fraction for the disk MHD generator and the Brayton turbo-generator is about the same (Table 6-1), therefore, the reactor thermal power is about the same. In this power range, the NDR is criticality limited so that changes in power levels have negligible impact on reactor size and mass. The power conversion inlet temperature is significantly higher for the disk MHD generator, so that with about the same energy extraction fraction, the flow rate for the MHD system is significantly less.

TABLE 6-1. OPEN CYCLE POWER SYSTEM CHARACTERISTICS

	NDR/MHD Disk	NDR/Brayton Turbo-generator
Power Conversion Energy Extraction, %	42	43
Power Conversion Inlet Hydrogen Temperature, K	2900	1700
Total Flow Rate, kg/s	5.55	9.07

A mass comparison of the two nuclear space power systems is given in Table 6-2. The power conversion MHD disk mass is from our recently completed Task 1 report[(6-1)] and the Brayton turbo-generator mass is scaled from reference 6-2. The miscellaneous items include piping, structures, auxiliary components and external shielding; the mass in this category is assumed to be the same for both systems.

The power conditioning components compose a large portion of the mass of the nuclear space power systems for both MHD and Brayton turbo-generator systems. The NDR/Brayton turbo-generator system has an advantage in dry mass at this power level. Improvements in disk MHD power conditioning integration/optimization (Section 4) can significantly reduce (~ 7000 kg) overall power system mass.

When both power systems must supply their own liquid hydrogen with a 1000 effective full power seconds (EFPS), which includes 40 startup/shutdowns, the range of wet mass variance ($\pm$ 20 percent) of the power system has considerable overlap. With further development in the disk MHD generator power conditioning, the disk MHD generator system with its own hydrogen supply system would be at a lower mass than a NDR/Brayton turbo-generator with its own hydrogen supply at a 1000 EFPS requirement.

(6-1) WAESD-TR-88-0002, Conceptual Design of a Space-Based Multimegawatt MHD Power System, Task 1 Topical Report (Draft), January 1988.

(6-2) WAESD-TR-87-0010, NERVA Derivative Reactor Brayton Space Power System Concepts for Multimegawatt Applications, March 1987.

TABLE 6-2. 100 MW_e OPEN CYCLE POWER SYSTEM MASS (kg) CHARACTERISTICS

	NDR/MHD Disk	NDR/Brayton Turbo-generator
Reactor	2200	2200
Miscellaneous	1570	1570
Power Conversion		
MHD Disk (+ Magnet)	3530	
Turbines		2000
Generators		2600
Power Conditioning		
Inverters	3100	
Transformers	8400	
Rectifiers & Filters	1700	1700
Cooling & Packaging	3700	500
Power System Dry Mass	24200	10570
Fluid System at 42% Extraction and 1000 EFPS	12600	21500
Power System Wet Mass	36800	32070

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15. **ABSTRACT--PURPOSE, SCOPE, APPROACH, RESULTS, CONCLUSIONS, SIGNIFICANCE: (MAXIMUM: 200 WORDS)**

This report supplements the Topical Report WAESD-TR-88-0002, "Conceptual Design of a Space-Based Multimegawatt MHD Power System," (Jan. 1988) in the following areas: design and performance, spacecraft integration, power conditioning, and subsystem/component development and testing. Key elements of the disk MHD concept are discussed and described, providing preliminary configuration and dimensional information and the initial estimate of the mass of the disk MHD generator.

16. **THIS WAESD-TN SHOULD BE DESTROYED AFTER ______ MONTH ______ YEAR.**

FORM AESD-00130A